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# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**SMALL UNMANNED AERIAL SYSTEM (SUAS) FLIGHT  
AND MISSION CONTROL SUPPORT SYSTEM (FMCSS)  
DESIGN**

by

Timothy G. Lamb

September 2006

Thesis Advisor:  
Second Reader:

Wolfgang Baer  
Edward Fisher

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**SMALL UNMANNED AERIAL SYSTEM (SUAS) FLIGHT AND MISSION  
CONTROL SUPPORT SYSTEM (FMCSS) DESIGN**

Timothy G. Lamb  
Lieutenant Commander, United States Navy  
B.S., University of Missouri-Rolla, 1995

Submitted in partial fulfillment of the  
requirements for the degree of

**MASTER OF SCIENCE IN INFORMATION TECHNOLOGY MANAGEMENT**

from the

**NAVAL POSTGRADUATE SCHOOL  
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## **ABSTRACT**

Unmanned Aerial Systems (UAS) are playing a significant role in the Global War on Terrorism (GWOT). Until recently, small UAS (SUAS) were an insignificant part of these efforts. Now their numbers exceed those of their larger counterparts by an order of magnitude. Future projections anticipate a growing demand for SUAS making now the best time to examine the functions they perform in order to make better decisions concerning their future design and development. This thesis provides a brief history of UAS and discusses the current capabilities and mission areas in which they perform. Their relevance to modern warfare and assumptions concerning their future roles on the battlefield is presented. Predominant UAS missions are identified, as well as the technical requirements deemed necessary for their success. A generic UAS functional model is developed to illustrate where the challenges and technology gaps manifest in SUAS design. Possible technology solutions that could fill these gaps are presented and a field experiment is conducted to demonstrate the feasibility of several possible solutions. The goal of this thesis is to identify existing technology gaps and offer technology solutions that lead to better design of future SUAS flight and mission control support systems (FMCSS).



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# **I. INTRODUCTION**

## **A. MISSION STATEMENT**

Unmanned Aerial Systems (UAS) are playing a significant role in the Global War on Terrorism (GWOT) and new missions are regularly generated for UAS as their capabilities continue to increase. Small UAS (SUAS) are quickly taking on a larger role in the GWOT and this trend is expected to continue. The capability of any given UAS determines the types of missions it can accomplish. These missions vary widely from Intelligence, Surveillance, Reconnaissance (ISR), precision target location, chemical/biological detection and measurement, force protection, combat search and rescue (CSAR), etc. The U.S. government, and hence the American public will spend considerable amounts of money to advance and leverage the potential of all UAS. In light of this, and the ever constrained budgets of the Department of Defense (DoD), developers and designers of UAS must strive to provide the most capability for the least amount of money, i.e., the most “bang-for-the-buck,” when these systems are ultimately implemented.

The strengths and weaknesses of UAS are a function of numerous known and unknown parameters such as aerodynamics of the UAV itself, sensor performance, ground control station (GCS) user interface, operator skill, weather conditions, radio control signal quality, etc. Knowledge of these strengths and weaknesses permits the development of technical requirements that enable UAS to effectively execute any given mission. This thesis will take a high level look at SUAS. An examination of the predominant missions and capabilities required in order to effectively execute those missions will be made followed by a discussion of the technical requirements needed to enhance the chances for mission success. Challenges impeding or preventing SUAS from being as effective as possible, such as high cost or unproven technology, are addressed along with recommendations to mitigate their effects. The goal of this thesis is to identify existing technology gaps and offer possible technology solutions that will aid the design of future flight and mission control support systems (FMCSS) for SUAS.

This thesis consists of three parts. The first, Chapters I and II, provides general background information on military UAS. Historical achievements over the past 40 years

are highlighted and their current mission areas and capabilities are introduced. The relevance of UAS in modern warfare is discussed including the growing significance that small UAS (SUAS) are playing in the GWOT. Warfighter requirements for UAS, and the priorities they give to various missions is documented. Part I also presents the assumptions made concerning future UAS development and the methodology followed in writing this thesis.

The second part, Chapters III through V, starts with a discussion of the challenges facing modern SUAS. Predominant UAS missions are presented in addition to the technical requirements deemed necessary for their success. A matrix of UAS missions versus functions is presented as a segue into the final chapter that concludes with a generic SUAS functional model illustrating UAS subsystems and the functions they perform.

Part three, Chapters VI through X, begins with a discussion of selected technology gaps that prevent SUAS from performing in an optimal fashion. This is followed by a chapter that identifies possible current and future technologies that could be utilized to address these gaps. Several possible technology solutions are investigated during a field experiment to demonstrate their feasibility. The thesis concludes with lessons learned and recommendations for the design of future SUAS Flight and Mission Control Support Systems (FMCSS).

## **B. BACKGROUND**

The military role of UAS is growing at unprecedented rates. Within the last calendar year, tactical and theater level unmanned aircraft (UA) alone, had flown over 100,000 flight hours in support of Operation ENDURING FREEDOM (OEF) and Operation IRAQI FREEDOM (OIF).<sup>1</sup> Rapid advances in technology are enabling more and more capability to be placed on smaller airframes which is spurring a large increase

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<sup>1</sup> Testimony of Mr. Dyke Weatherington, Deputy, UAS Planning Task Force, before the House of Representatives Committee on Transportation and Infrastructure, Subcommittee on Aviation; March 29, 2006.

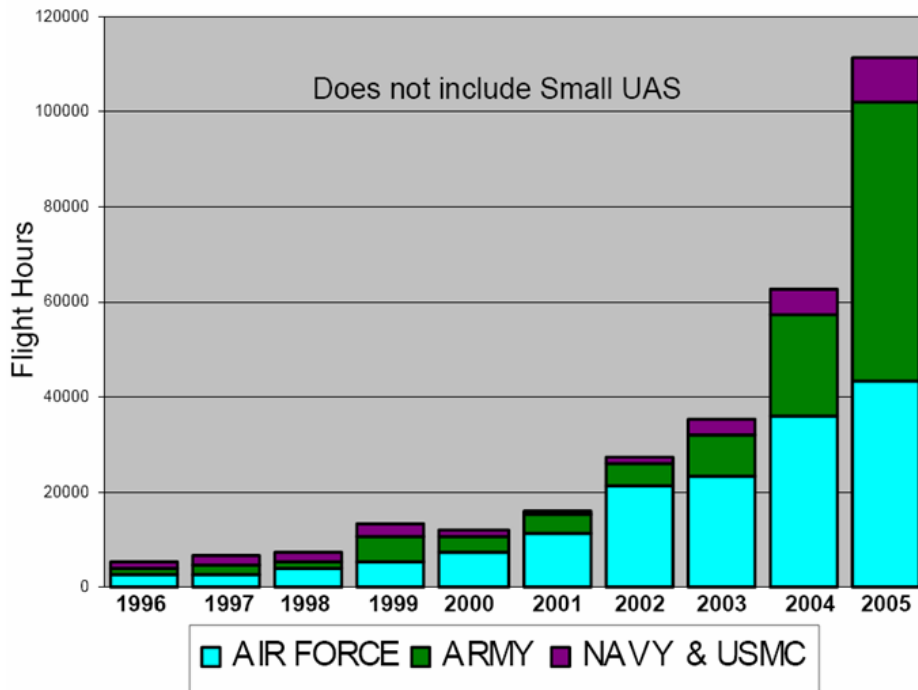


Figure 1. DoD UAS Flight Hours (From: Office of Secretary of Defense)

in the number of SUAS being deployed on the battlefield. The use of SUAS in combat is so new that no formal DoD wide reporting procedures have been established to track SUAS flight hours. As the capabilities grow for all types of UAS, nations continue to subsidize their research and development leading to further advances enabling them to perform a multitude of missions. UAS no longer only perform intelligence, surveillance, and reconnaissance (ISR) missions, although this still remains their predominant mission. Their roles have expanded to areas including electronic attack (EA), strike missions, suppression and/or destruction of enemy air defense (SEAD/DEAD), network node or communications relay, combat search and rescue (CSAR), and derivations of these themes. UAS range in cost from a few thousand dollars to tens of millions of dollars, and the aircraft used in these systems range in size from a Micro Air Vehicle (MAV) weighing less than one pound, to large aircraft weighing over 40,000 pounds.

### C. UAS RELEVANCE

The term “UAS” is relatively new and reflects the new perception given to a system that was once only thought of in terms of the unmanned vehicle itself. During the 1950s these “systems” were used as targets for other weapons, usually missiles, to shoot

at, and referred to as drones. They were also being deployed as decoys with a boxy design in order to give them a radar cross section much like that of their B-52 mother ships. Some were fitted with active radar reflection enhancement devices, as well as chaff and flare dispensers to further confuse enemy defenses. These decoys were also equipped with an autopilot system that could be programmed for one change of speed and two turns. The success of drones and decoys naturally led to more advanced missions. In 1959, Ryan Aeronautical began testing to evaluate the viability of using UAS for reconnaissance missions. These efforts led to the deployment, in 1964, of an Air Force reconnaissance UAS called Lightning Bug to take pictures over China. Two Lightning Bugs were launched from a DC-130 to fly over China and back to Taiwan where they would be recovered from a rice paddy field after deployment of parachutes. One of the Lightning Bugs failed to launch and the other one was badly damaged after splashdown when it was dragged over the ground by its parachute. The navigation of these unmanned aircraft was not as accurate as predicted, but the film payload was recovered intact and images of several primary targets were recovered. Lightning Bugs were also used by the U.S. Navy over Vietnam to conduct reconnaissance missions.



Figure 2. Lightning Bug UAS (From: Unmanned Aerial Vehicles (UAVs) An Assessment Of Historical Operations And Future Possibilities; Maj. Christopher A. Jones, USAF; Air Command and Staff College, Research Paper, March 1997)

After Vietnam, the use of UAS in the U.S. military rapidly declined. It has taken over two decades for UAS to reemerge as a significant player in the U.S. military. However, recent battlefield successes have practically ensured their long term survival. During Desert Shield/Storm, the Pioneer, a derivative of an Israeli surveillance and reconnaissance UAS, played a crucial role for Army, Navy and Marine Corps battlefield



commanders. They were so effective that Iraqi troops began to associate the sound of the UAV's two-cycle engine with an imminent destructive bombardment. UAS operations throughout the conflict led to the first recorded instance of soldiers surrendering to a robot.

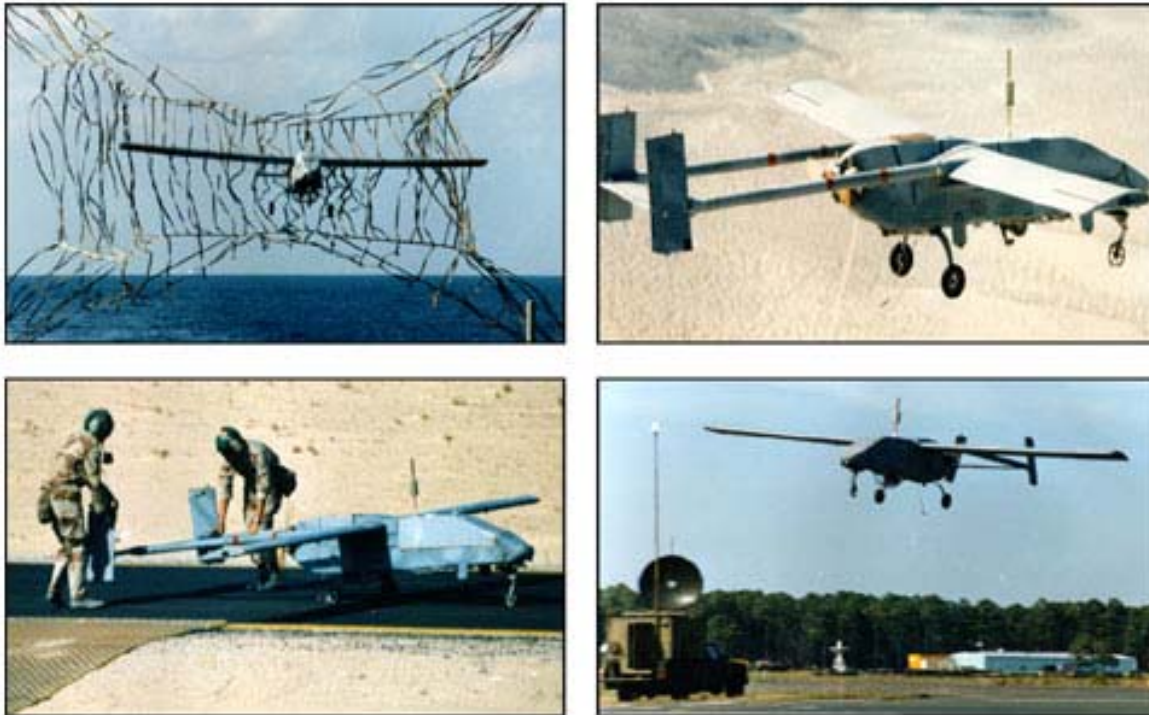


Figure 3. Pioneer UAS

During Operation Iraqi Freedom (OIF), UAS have continued to play an important role becoming the most-requested capability among combatant commanders in Southwest Asia according to the deputy director of the Pentagon's UAS planning task force<sup>2</sup>. In terms of raw numbers, there is an order of magnitude more small UAVs (SUAV) in the battlespace compared to the larger tactical and theater-level UAVs. As of this writing, DoD has a force of over 2600 SUAVs and over 300 tactical and theater-level unmanned aircraft (UA) supporting military operations worldwide.<sup>3</sup> The most prevalent UAS in the

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<sup>2</sup> *Unmanned Aircraft Gain Starring Role in Terror War*, News article by Donna Miles, American Forces Press Service, November 9, 2004.

<sup>3</sup> Testimony of Mr. Dyke Weatherington, Deputy, UAS Planning Task Force, before the House of Representatives Committee on Transportation and Infrastructure, Subcommittee on Aviation; March 29, 2006.

Iraqi theater is the SUAS called Raven. It functions primarily as an intelligence, surveillance and reconnaissance platform that provides warfighters real-time, over-the-horizon views of trouble spots. It is a hand-held system that packs into a transit case which can fit into the back of a High Mobility Multipurpose Wheeled Vehicle (HMMWV).



Figure 4. Hand-Launching Raven

#### **D. ASSUMPTIONS**

UAS will continue to be a major player in the current Global War on Terrorism (GWOT) and battlefield commanders will increasingly request their capabilities. Advances in materials technology and computer hardware and software will significantly increase the capabilities available in UAS. Advances in microelectronics will particularly benefit SUAS since computer hardware components will become lighter permitting their installation on the smaller UAV platforms. New software solutions will need to be developed to exploit the increasing capability made available by the new computer hardware components. This rapid technology growth will accelerate government spending on UAS (Figure 5) and beg leadership to find ways to standardize components and operational procedures to keep these systems within affordable windows. At some point the cost of SUAS may reach the point that the SUAV become an expendable part of the overall system.

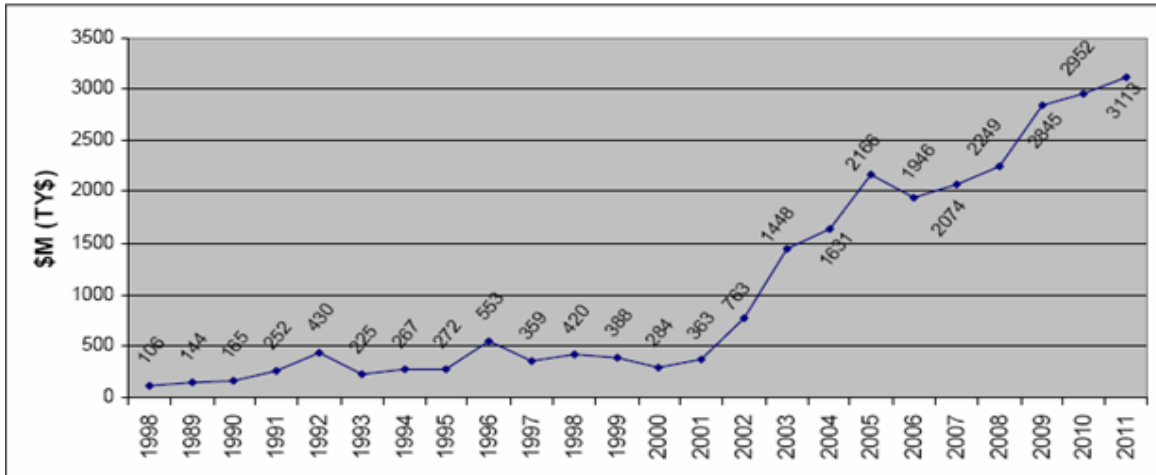


Figure 5. DoD Annual Funding Profile for UAS (From: UAS Roadmap, 2005)

## E. METHODOLOGY

Research will be conducted on the existing literature that pertains to military UAS. This research will uncover the most important and most probable missions that UAS are currently performing. It will determine the most likely missions these systems will be called upon to perform in the future. The capabilities required or desired to perform these missions will be discovered through literature review and interviews with subject matter experts (SME). A mission versus functions matrix will be presented as a guide to ascertain the technology requirements necessary to effectively perform the most likely missions of UAS with an emphasis on missions performed by SUAS. A “hands-on” field experiment conducted at McMillan Airfield on Camp Roberts California National Guard Training Site to test a possible future SUAS technology is presented. Based on the research findings in this thesis, systems engineering methodology is applied to develop functional requirements from the mission needs that were documented in the literature review, SME interviews, and Camp Roberts field experiment.

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## II. UAS MISSION AREAS AND PRIORITIES

### A. BACKGROUND

UAS have proven their ability to be force multipliers—that is, devices that improve effectiveness in combat without requiring more forces or that enable commanders to accomplish missions with fewer forces. History has validated the worth of UAS, large and small, in a variety of different roles. This chapter will briefly examine the historical roles of UAS within the last 40 years in the U.S. military and then move on to examine the current capabilities and predominant missions that UAS provide today. COCOM requirements and priorities are also investigated as their input comes directly from the warfighters actually using UAS today. Their experiences and feedback will provide the direction and focus needed to design the next generation flight and mission control support systems (FMCSS).

### B. HISTORICAL UAS MISSION AREAS

There exists a strong correlation with past UAS missions and the missions currently being filled by UAS today. Over the past 40 years, the Services have extensively utilized UAS to provide five variations of the intelligence, surveillance, and reconnaissance (ISR) role. This consistency indicates that the underlying requirements are long-term, and there is no reasonable reason to expect that this trend will cease. Table 1 illustrates the historically validated roles of UAS.

<b>UAS Role:</b>	Brigade/division asset for RSTA
Proponent:	Army, Marine Corps
Heritage:	Falconer (1950-60s) – Aquila (1970-80s) – Pioneer (1980-2000s)-Dragon Drone (1990s) – Outrider (1990s) – Shadow 200 (2000s)
<b>UAS Role:</b>	Shipborne asset for reconnaissance and weapon support
Proponent:	Navy
Heritage:	DASH (1960s) – Project Blackfly (1970s) – Pioneer (1980-2000s) – Fire Scout (2000s)
<b>UAS Role:</b>	Small unit asset for over-the-hill reconnaissance
Proponent:	Marine Corps
Heritage:	Bikini (1960s) – Pointer (1980-90s) – Dragon Eye (2000s)
<b>UAS Role:</b>	Survivable asset for strategic penetrating reconnaissance
Proponent:	Army/Air Force/Navy
Heritage:	Osprey (1960s) – D-21 (1960s) – Classified Program (1980s) – DarkStar (1990s) – JUCAS (2000s)
<b>UAS Role:</b>	High altitude endurance asset for standoff reconnaissance
Proponent:	Air Force
Heritage:	Compass Arrow (1960s) – Compass Dwell (1970s) – Compass Cope (1970s) – Condor (1980s) – Global Hawk (1990-2000s)

Table 1. Historically Validated UAV Roles (From UAS Roadmap, 2005)

### **C. CURRENT UAS MISSION AREAS**

ISR utilizing electro-optical (EO), infrared (IR) and more recently, small aperture radar (SAR) sensors, have been the historically predominant roles or mission areas of UAS over the last 40 years. The GWOT, however, has demonstrated the value of UAS in many other mission areas not strictly related to ISR. Table 2 on the following page shows a list of 15 other mission areas, in addition to ISR, where UAS have flown in proof-of-concept demonstrations. Notice that the list gives a demonstration of UAS based on whether the mission is “dull,” “dirty” and/or “dangerous.” An example of a “dull” mission could be a very long ISR mission such as a no-fly zone patrol. It is important to point out, however, that although the UAS sensors may be just as alert in the last hour of its patrol as it was in the first hour, this may not alleviate the dull aspect of the mission since a human operator may still be required to monitor and evaluate the incoming intelligence data. The underlying assumption of good FMCSS design is that cognitive aids would be available to identify situations of interest that would help to mitigate the “dullness.” “Dirty” missions (and also dangerous) could involve flights into airspace potentially contaminated with biological or chemical agents. These areas would be avoided if possible, but if the mission was important enough, the UAV could operate in areas impossible for manned aircraft and either be decontaminated or discarded at mission completion. An example of a “dangerous” mission, but not considered “dirty” is the electronic attack (EA) mission. EA missions are often performed early in a battle while the enemy’s air defenses pose a serious threat.

### **D. REQUIREMENT OF UAS**

Each year every COCOM submits an integrated priority list (IPL) of requirements identifying gaps in the warfighting capabilities within their Area of Responsibility (AOR). At SECDEF direction, the latest list identifies capability gaps reflective of the five 2002 QDR-defined “operational risk” categories of battlespace awareness (BA), command and control (C2), focused logistics (FL), force application (FA), and force protection (FP)<sup>4</sup>. The latest IPL, covering fiscal years 2006 through 2011, specifies 50 gaps, 27 of which (54 percent) are currently, or could potentially be, addressed by UAS.

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<sup>4</sup> Unmanned Aircraft Systems Roadmap 2005-2030, 4 August 2005, Office of the Secretary of

Requirements	Justification for UA Use			UA Experience
(Mission Areas)	“Dull”	“Dirty”	“Dangerous”	(UA/Payload, Place Demonstrated, Year)
ISR	x		x	Pioneer, Exdrone, Pointer/Gulf War, 1990-91 Predator, Pioneer/Bosnia, 1995-2000 Hunter, Predator, Pioneer/Kosovo, 1999 Global Hawk, Predator, /Afghanistan, Iraq 2003 – Present Hunter, Pioneer, Shadow/Iraq-2003-Present
C2/Communications	x			Hunter/CRP, 1996; Exdrone/TRSS, 1998 Predator/ACN, 2000
Force Protection	x	x	x	Camcopter, Dragon Drone/Ft Sumner, 1999 FPASS, Dragon Eye, Pointer, Raven, Scan Eagle/Iraq -Present
SIGINT	x		x	Pioneer/SMART, 1995 Hunter/LR-100/COMINT, 1996 Hunter/ORION, 1997 Global Hawk/German Demo, 2003; Iraq, 2004 - Present
Weapons of Mass Destruction (WMD)		x	x	Pioneer/RADIAC/LSCAD/SAWCAD, 1995 Telemaster/Analyte 2000, 1996 Pointer/CADDIE 1998 Hunter/SAFEGUARD, 1999
Theater Air Missile Defense (TAMD)	x		x	Israeli HA-10 development, (canceled) Global Hawk study, 1997
SEAD			x	Hunter/SMART-V, 1996 Hunter/LR-100/IDM, 1998 J-UCAS/TBD
Combat Search and Rescue (CSAR)			x	Exdrone/Woodland Cougar Exercise, 1997 Exdrone/SPUDS, 2000
Mine Counter Measures (MCM)			x	Pioneer/COBRA, 1996 Camcopter/AAMIS, 1999 (Germany)
Meteorology and Oceanography (METOC)	x	x	x	Aerosonde/Visala, 1995 Predator/T-Drop, 1997 Predator/BENVINT ACTD, 2002
Counter Narcotics (CN)	x		x	Predator/Ft Huachuca, 1995 Pioneer/So. California, 1999 Hunter, Shadow/Ft Huachuca, 2003-2004
Psychological Ops			x	Tern/Leaflet Dispensing, 2004
All Weather/Night Strike			x	DASH/Vietnam, 1960s Predator/Afghanistan/Iraq, 2001 Global Hawk/Iraq, 2003
Exercise Support	x			Predator/Joint Operational Test Bed System (JOTBS), 2002
Anti Submarine Warfare	x			DASH, 1960s
Navigation	x			Hunter/GPS Pseudolite, 2000
Table is not all inclusive				

Table 2. UAS Mission Areas (From UAS Roadmap, 2005)

Defense, p. 43.

Table 3 from the 2005 Roadmap shows the COCOM priorities for the 27 capability gaps on a 1-8 priority scale.

Priority	CENTCOM	EUCOM	JFCOM	NORTHCOM	NORAD	PACOM	SOUTHCOM	SOCOM	STRATCOM	STRACOM
1										
2										
3										
4										
5										
6										
7										
8										

Table 3. IPL for UAS-Related Applications by COCOM

Solid colored blocks indicate missions that UAS perform today and shaded blocks indicate functions that are under development. It should be observed that every COCOM places UAS applications in the top half of his/her priority list. Additionally, UAS applications are the #1 priority in five of nine COCOM including NORAD, and every mission currently performed by UAS (solid blocks) is listed within the top three priority. Clearly, UAS have been proving their value in modern warfare and will increasingly do so as their functionality improves.

## E. UAS MISSIONS

### 1. Surveillance, Target Acquisition and Reconnaissance (STAR)

Surveillance, Target Acquisition and Reconnaissance (STAR) are by far the predominant missions of UAS today. As mentioned in Chapter I, these missions date back to the Lightning Bug UAS used in 1964 over China and shortly thereafter in Vietnam. STAR missions can be described in terms of three categories: “standoff,” when missions are conducted while recognizing the sovereign airspace of other countries; “overflight,” when missions are flown in the sovereign airspace of another nation, with or without consent, but at low risk to the mission; and finally, “denied,” which is similar to “overflight” except the nation-state being flown against possesses a credible capability to deny access to their territory<sup>5</sup>. Strategic national assets such as satellites are also used for

<sup>5</sup> Unmanned Aircraft Systems Roadmap 2005-2030, 4 August 2005, Office of the Secretary of Defense, p. A-2.



“denied” missions but they have the disadvantage of predictability. UAS can augment satellites by showing up unwarned at unpredictable times allowing commanders to collect information when an adversary least expects it.

Standoff missions are usually conducted during peacetime. They are also used when the probability of vehicle loss or political ramifications are too great to risk the exposure of the UAV to detection. To achieve the effect of persistence, the UAV must have the capability to remain on station for long periods of time. Often broad areas need to be covered requiring high altitude flights with long range sensor performance. In these cases, larger UAVs capable of long endurance and the ability to carry heavier payloads are needed. These systems may be significantly hard pressed to collect weak electromagnetic signals or take high resolution photographs due to a large standoff distance. In these cases SUAS can place sensors closer to the desired area of interest and thus increase chances of mission success may be the best option. These missions essentially become that of an overflight mission discussed next.

Overflight missions occur with or without the knowledge and/or consent of another state or entity being monitored. Many overflight missions are being conducted today in both Afghanistan and Iraq in support of the GWOT. The UAV may fly at high, medium or low altitudes depending on the particular situation. If persistence is needed and image resolution or signal collection can be accomplished from high altitude, then a larger high altitude long endurance (HALE) platform such as the Global Hawk or Predator could be chosen. If poor weather prevents operation from high or medium altitude then a SUAS could be utilized. There is no particular standard platform to use when conducting overflight missions as there are for standoff and denied access missions.

Denied access missions are generally used in support of combat operations or national security requirements. In many cases satellites can be used, but as mentioned earlier, the disadvantage with satellites lay in their predictability. An adversary can prevent data collection or deliberately deceive intelligence gatherers by placing targets or signals in the area of interest precisely when a satellite is scheduled to reconnoiter. Manned systems, most notably the U-2 and SR-71, and more recently the EP-3, have also been used for denied access missions. The drawback with these platforms lie in their

potential risk of losing the aircrew and/or an expensive aircraft as well as the adverse political fallout that could result from its detection or capture. UAS mitigate most of these concerns: they can arrive unwarned, have no crew to place in danger, are much less expensive than their manned counterpart and, being unmanned, they pose significantly less diplomatic consequences if captured. The 2003 Defense Science Board and 2003 Air Force Scientific Advisory Board results both reported that a UAS capable of unwarned collection is needed by DoD.

The idea of using SUAS for STAR missions, while not new, is still an emerging concept worthy of greater study. Encouraging results have been achieved using SUAVs to collect against weak signals and to obtain high resolution images. Definitive answers have not been determined to decide if multi-mission, versus dedicated mission, platform designs are the most cost effective approach for every application. It is expected that opportunities which take advantage of growing commercial markets will yield the best value to DoD and ultimately to the taxpayers.

## **2. Electronic Attack (EA)**

Electronic Attack (EA) is the use of electromagnetic (EM) energy to reduce the effectiveness of RADAR systems to allow flight of aircraft without harm from radars and associated missiles. In this context, EA of an integrated air defense system (IADS) can be considered to be part of *disruptive* SEAD discussed in the next section. EA can be achieved by either distracting a RADAR with confusing or deceptive information, or by blinding the RADAR making it unable to detect, track, engage, or destroy threats.<sup>6</sup>

Only recently have UAS been used to conduct EA. Prior to this, EA involved specially designed manned aircraft such as the Navy EA-6B Prowler and the Air Force EF-111 Raven. Because UAS can achieve theoretically higher levels of survivability than manned aircraft, they offer a desirable alternative for conducting EA missions to manned aircraft. SUAS are also well suited for EA attack missions due to their small size. They are naturally stealthy making them less susceptible to detection and more likely to get close up to an adversary's radar. Current research is being conducted at NPS on a Morphing Micro Air and Land Vehicle (MMALV) that can fly and crawl up to a

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<sup>6</sup> Cooperative Electronic Attack using Unmanned Air Vehicles, Mark J. Mears, 2006, Air Force Research Laboratory, Air Vehicles Directorate, Wright Patterson AFB

predetermined target (Figure 6). Getting close to a radar antenna significantly reduces the amount of power required to interfere with the radar system. Using UAS to perform EA missions will likely require more autonomy than most UAS currently have. Desirable capabilities would include the ability to operate and handle aircraft related and mission-related contingencies while unable to communicate with the MCS due to self-jamming and beyond line-of-sight (BLOS) operations.



Figure 6. NPS MMALV (From: wingspan < 30.5cm, weight < 450g)

### **3. Strike/SEAD**

On February 21, 2001 an Air Force Predator UAV made history by successfully aiming and launching a ‘live’ Hellfire-C, laser-guided missile that struck an unmanned, stationary Army tank on the ground at Indian Springs Air Force Auxiliary Airfield near Nellis Air Force Base, NV. Since then, the RQ-1 Predator has been modified to accomplish a ground attack role as well as reconnaissance and was redesignated the MQ-1B Armed Predator. On November 4, 2002 in Yemen, a Predator UAV was used to drop a Hellfire missile which destroyed a civilian vehicle carrying six suspected Al-Qaida terrorists one of whom was a key suspect in the October 2000 attack on the U.S. Navy destroyer Cole. Due to the endurance and surveillance capability required to successfully carry out these missions, some have referred to such missions as a subset of the strike mission and have called it “armed reconnaissance.” Either way, it is the strike capability that clearly differentiates these missions from others. They provide an attractive alternative to manned aircraft because they eliminate the risk of the loss of an aircrew.

Strike mission targets may be heavily or lightly defended and the level of the adversarial threat determines the characteristics most important in the UAS to carry out a

strike mission. If the target is heavily defended, survivability is paramount. The system design would trade payload and endurance characteristics for attributes that increase its probability of success against highly defended targets. For targets less heavily defended, more emphasis would be justified on payload (sensors) and endurance which would lead to the most efficient “kill” capability. Currently, no SUAS have been designed to carry out strike missions.

SEAD missions can be either destructive or disruptive. In military doctrine, *destructive* SEAD means destruction of the target in a permanent way and has the appropriate acronym DEAD for destruction of enemy air defense. When the mission calls for neutralizing a radar temporarily, it is called *disruptive* SEAD. Destructive SEAD missions could be considered a subset of a strike mission and disruptive SEAD missions could be considered a subset of the EA mission. The characteristic that differentiates the SEAD mission from strike or EA is the target.

SEAD are categorized as either pre-emptive or reactive. Pre-emptive SEAD describes employment of the UAS prior to a strike aircraft’s arrival. Its job is to suppress or destroy the enemy’s air defenses in order to protect the strike aircraft from surface to air attack. Reactive SEAD missions involve the rapid suppression or destruction of enemy air defenses that become visible, or “pop-up,” during mission execution. Regardless of mission type, to be effective the UAV will have to “close-in” on the enemy threat. Attributes of speed, maneuverability and stealth will be highly desired to enhance vehicle survivability. Various design criteria deserve future study to determine the ideal combination of capabilities required for destructive SEAD missions.

The 2005 UAS Roadmap has identified several characteristics that UAS accomplishing pre-emptive SEAD missions should have and are presented below.<sup>7</sup>

- Extremely high mission reliability, as follow-on force assets (many of which will be manned) will depend upon the protection of a SEAD UA asset.
- Battle damage assessment (BDA) so operational commanders can properly determine whether strike “go/no-go/continue” criteria have been met.

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<sup>7</sup> Unmanned Aircraft Systems Roadmap 2005-2030, 4 August 2005, Office of the Secretary of Defense, p. A-6.

- If BDA is organic this reduces the reliance on other systems outside the SEAD UA platform, but puts other design requirements on the SEAD UA that complicate signature control.
- If BDA is not organic then this simplifies the SEAD UA design requirements, but complicates the integration of other ISR capabilities as a family of systems attempting to achieve effect in the SEAD mission.
- Weapons optimized for concept of employment. If using direct attack munitions (short range), then a robust signature reduction design, or stand-off weapons with appropriate support from on-board or off-board sensors to find, fix, track and target intended threats must be employed.
- The use of direct attack munitions is a major cost avoidance compared to the integration and use of stand-off weapons.
- However, stand-off weapons provide an opportunity to relax signature design requirements and thus avoid significant low-observable costs.

Execution of the reactive SEAD mission implies further design criteria:

- Enemy defensive systems' operations must be detected rapidly implying an onboard capability to detect threats, or a well integrated system of systems.
- Reaction time from detection to neutralization of the enemy defenses must be very short (seconds).
- When using weapons to neutralize defenses, the flight time of the weapon must be reduced by the ability to stand in close to the target (high survivability) or by the use of a high-speed weapon.
- Robust, anti-jam, data links are required.
- Reactive SEAD will require low latency human interaction with the system – or high autonomy within the system for determination of ROE criteria.
- Reactive SEAD implies the integration of manned and unmanned aircraft in a single strike event.

#### **4. Network Node/Communications Relay**

Multiple UAS have the ability to provide non-line-of-sight (NLOS) communication links to ground units, and thus have the ability to provide value to operational and tactical level commanders. UAVs can act as flying network nodes with having the capacity to relay large quantities of data. For example, it is possible using small (~8 in.) directional antennas, to exchange about 10 gigabits per second (Gbps)

between high-altitude UAVs and surface stations, over typical slant ranges, using only 1 W of radiated power<sup>8</sup>.

UAS conducting Network node/Communications Relay missions must be capable of flying at sufficient altitude in order to maintain a link for the duration of the mission. There must be sufficient redundancy built in to the system to provide continuous connectivity and the vehicle must be capable of generating adequate power, perhaps through the use of solar arrays, to provide the required data throughput capacity. Radio line of sight (LOS) increases with sensor height i.e., aircraft altitude, as shown Figure 7 below. Medium and high altitude UAVs have the ability to fly above bad weather and maintain communication with each other while hundreds of miles apart.

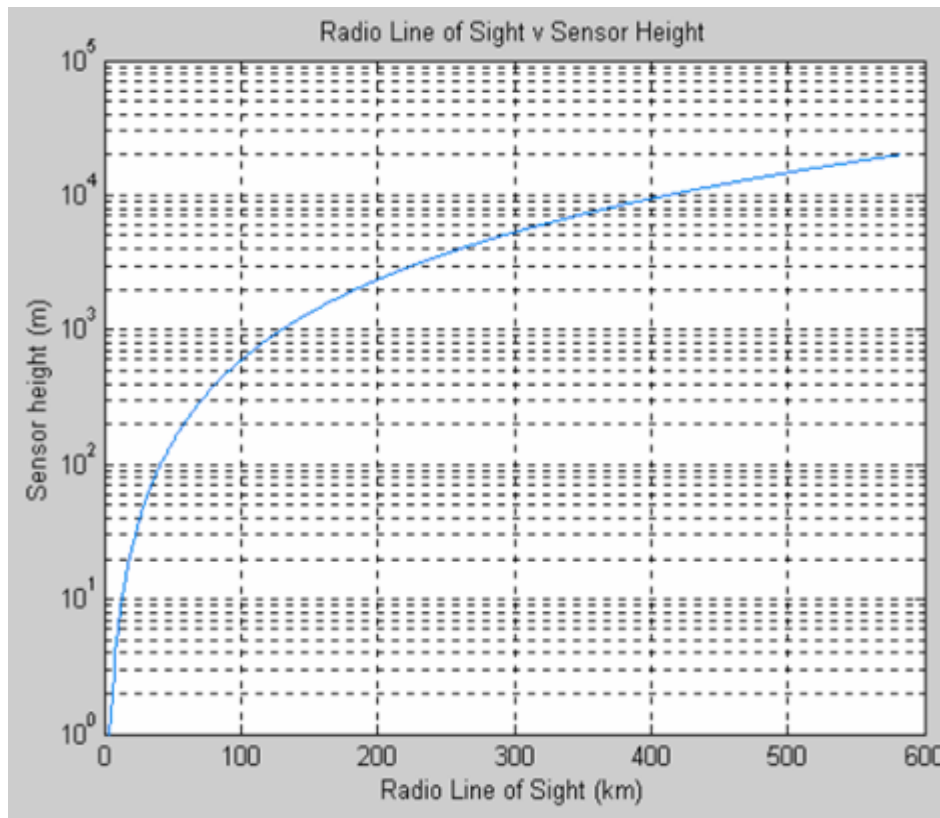


Figure 7. Radio LOS vs. Altitude (From: Miniature UAV's & Future Electronic Warfare, Dr Anthony Finn, Dr Kim Brown, Dr Tony Lindsay; Technical Paper, October 2002.)

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<sup>8</sup> Autonomous Vehicles in Support of Naval Operations, The National Academies Press, 2005, p. 39.

Network node/communications relay missions are relatively new for UAS but rapid progress is being made in this area. For example, in 2004, a long-endurance tactical UAV, the ScanEagle, successfully demonstrated the ability to relay high-speed wireless communications. Streaming video and voice-over IP communication was sent from a GCS over a secure high-bandwidth network to the ScanEagle 18 miles away. The data was then instantaneously relayed to ground personnel six miles from the UAV.<sup>9</sup> Other development work underway includes trials to use Global Hawk, a HALE UAS, and Predator, a MAE UAV, as airborne communications nodes to shorten sensor to shooter timelines utilizing beyond line of sight connectivity.<sup>10</sup> Due to the broad user base that could have access to network node/communications relay missions, the 2005 Roadmap predicts that any airborne communications node is likely to be a “Joint Program.” It further states that the inclusion of legacy formats and architectures will be established in any approved requirements document and receive input from the Assistant Secretary of Defense for Network Integration.<sup>11</sup>

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<sup>9</sup> Boeing news release dated 21 December, 2004; accessed 29 May 2006 at [http://www.boeing.com/news/releases/2004/q4/nr\\_041221n.html](http://www.boeing.com/news/releases/2004/q4/nr_041221n.html)

<sup>10</sup> Mission Applications and Concepts of Operations, R.A. Frampton, 2003.

<sup>11</sup> Unmanned Aircraft Systems Roadmap 2005-2030, 4 August 2005, Office of the Secretary of Defense, p. A-8.

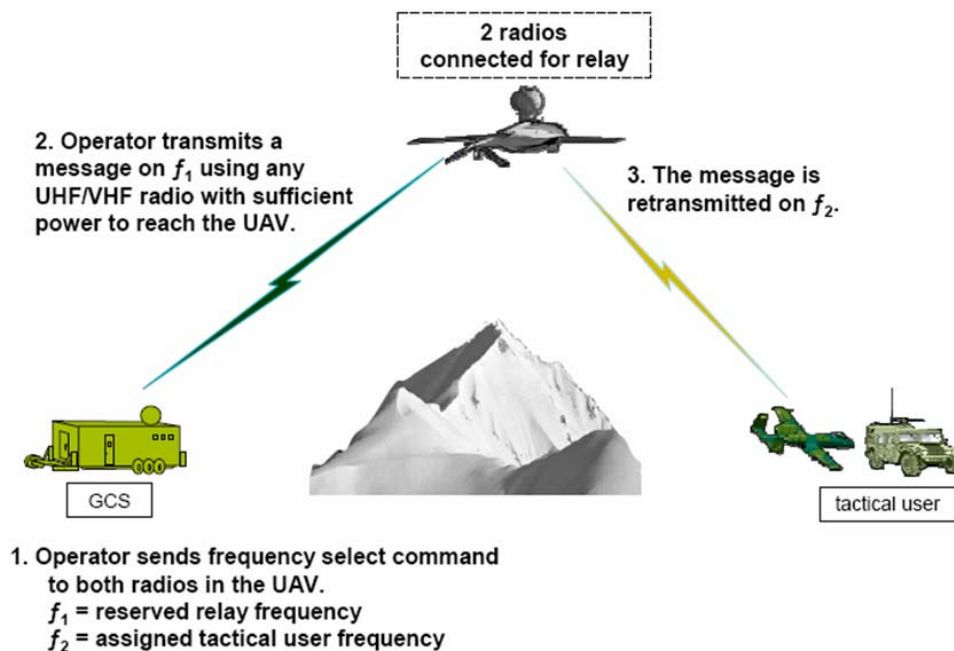


Figure 8. Communications Relay (From: Joint Unmanned Aerial Vehicle in Time-Sensitive Operations Joint Test and Evaluation Final Report, March 2005.)

## 5. Combat Search and Rescue (CSAR)

Joint Publication 3-50.21 discusses joint tactics, techniques, and procedures (TT&P) for combat search and rescue (CSAR) and defines CSAR as reporting, locating, identifying, recovering, and returning isolated personnel to the control of friendly forces in the face of actual or potential resistance. CSAR missions can become complex requiring the coordination of multiple participants of different services and hence the planning for these missions is accomplished at the Joint Search and Rescue Center (JSRC) under the direction of the Joint Force Commander (JFC). Integration of UAS into CSAR missions is so new (or Joint Pub 3-50.21 so old) that the Joint Publication does not even refer to UAS in their execution.

In general, UAS performing CSAR missions perform tasks similar to those involved in STAR missions. Their targeting capability is used to locate and provide the coordinates of the missing forces or indicate safe helicopter landing zones, parachute landing zones, or drop zones. If the isolated personnel are equipped with man-pack



radios, the UAV, acting as a network node, could become a communication relay allowing the isolated personnel to communicate with the JSRC.

SUAS could be used for CSAR missions at the small unit level requiring little or no coordination with higher headquarters. Their small size makes them difficult for the enemy to target and would not give away the friendly force's location. SUAS can help squad and platoon sized units search greater areas of terrain than would otherwise be possible in the same time with ground patrols. Their "eyes in the sky" vantage point also makes it easier to locate wreckage that might be missed on foot. In the future, it is expected that multiple SUAS operating in a coordinated net-centric environment will provide effective CSAR mission capability to commanders at both the tactical and operational levels.

Operating SUAS for CSAR missions does present limitations. SUAVs are limited by endurance and their lower altitudes may present larger acoustic and visual signatures making them susceptible to attack by man-portable air defense systems or otherwise alerting the enemy to friendly force locations. It is worth noting, however, that detection of SUAVs is still not easy even when looking for them. Discussion with operators and personal experience has revealed that it is difficult to hear SUAVs (gasoline or electric powered) even as low as 500 feet. One operator reported that after hearing a SUAV—the electric powered CyberBug; it was very hard to detect with the naked eye at 500 feet, and virtually impossible to detect at 1000 feet.<sup>12</sup> De-confliction issues should also be considered. Larger UAVs, such as Predator or Hunter, fly at altitudes common to fixed-wing aircraft; smaller UAVs, such as Raven and Dragon Eye, typically fly in rotary-wing airspace.

## **F. MISSION PRIORITIES**

In 2004 the Joint Chiefs of Staff asked each COCOM and Service to rank the importance of 18 missions relative to four general classes of UAS, small, tactical, theater, and combat. Their rankings were consolidated into a single chart and are provided in Table 4 below. Of note in the chart is the fact that reconnaissance missions are the #1

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<sup>12</sup> Discussion with Ed Fisher concerning his experience with CyberBug operations during daylight operations in Thailand.

mission priority across all four classes of UAS. Additionally, precision target location and designation missions are listed as the number two priority in all but one class of UAS (Theater) where it ranks as third.

Mission	Small	Tactical	Theater	Combat	JFC
Reconnaissance	1	1	1	1	BA
Signals Intel	10	3	2	5	BA
Mine Detection/CM	7	11	13	14	FP
Precision Target Location and Designation	2	2	3	2	FA
Battle Management	4	10	4	7	C2
Chem/Bio Reconnaissance	3	7	6	9	BA
Counter Cam/Con/Deception	8	5	7	11	BA
Electronic Warfare	14	9	10	4	FP
Combat SAR	6	8	8	10	FA
Communications/Data Relay	5	6	5	8	C2
Information Warfare	15	12	11	6	FA
Digital Mapping	11	13	9	12	BA
Littoral Undersea Warfare	17	15	14	13	FA
SOF Team Resupply	9	16	17	16	FL
Weaponization/Strike	16	4	12	3	FA
GPS Psuedolite	18	18	15	18	C2
Covert Sensor Insertion	12	14	16	15	BA
Decoy/Pathfinder	13	17	18	17	FA

Table 4. 2004-COCOM/Service UAV Mission Prioritization

### **III. PROBLEM DEFINITION**

#### **A. INTRODUCTION**

UAS, and in particular, SUAS are new technologies with vast potential that is just beginning to be discovered and exploited. Reflective of technologies still under development and the limited recent use of SUAS in operational environments, many areas for improvement have been revealed. This chapter will identify and investigate some important challenges to be addressed in designing future SUAS FMCSS.

There is no shortage of challenges and problems that remain to be solved in the field of UAS. This study could have narrowly focused on one particular problem or taken a very broad overarching view of UAS architecture. In this chapter we stay somewhere in between by addressing three areas in enough detail to guide future SUAS FMCSS design, but not so technical as to get lost in the weeds. The three broad areas to be examined are:

- Visual display
- Interoperability
- Logistics/Manpower/Training
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#### **B. VISUAL DISPLAY**

In the previous chapter we discovered that reconnaissance ranked as the most of important of 18 different types of missions that UAS either could or should perform. For SUAS, the majority of the data provided in these missions is image data collected from electro-optical (EO) cameras. The UAV flies within some distance of a potential target and collects visual data that is relayed to operators at the MCS. Human operators are tasked with reviewing the visual data collected to determine if there exist targets of interest to be acted upon. The quality of the video displayed directly affects the decisions operators make in the field. Several challenges associated with visual data from EO sensors have been observed.

- Time to detect target
- Target geo-location
- Image stability

- Narrow field of view (FOV)
- Unknown search history

### **1. Time to Detect Target**

As a UAV camera points to an area and collects optical information, this data is passed to the MCS in near real time (NRT). An operator, therefore, must be able to view this data and make decisions based on his or her observation of the incoming visual data. As the rate of visual data flow increases, human operators find it harder to identify a given target of interest since the target remains in view for smaller amounts of time. In one target detection experiment (Itti, Gold, and Koch, 2001), the participants were instructed to detect a target in a natural scene photograph; a task similar to UAV search task. The average time required for target detection was 2.8 seconds. When UAV operations lead to a high rate of video flow, the target may not remain visible on the monitor for 2.8 seconds.

### **2. Target Geo-location**

Once a target has been detected, the next logical question to be asked is, “where is it?” Target location in terms of geographical coordinates is an important capability for several military missions. This functionality improves situational awareness (SA) and begins to turn raw data into actionable intelligence. At least three missions identified in Chapter Two require the UAS to provide geo-located target coordinates. For SUAS utilizing EO cameras, identifying the precise location of a target with geographical coordinates is not trivial.

### **3. Image Stability**

Unstable imagery is a problem with SUAS due to the “bounce” encountered with air turbulence. During SUAS experiments at Camp Roberts, California, observers noted large oscillations of the video frame displayed at the ground control station (GCS) at a frequency of approximately 2-4 oscillations per second. For example, if an object were at the top of the monitor image, it would go near, or off, the bottom of the monitor image several times per second.<sup>13</sup>

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<sup>13</sup> Human Systems Integration and Automation Issues in Small Unmanned Air Vehicles; Michael E. McCauley, Panagiotis Matsangas; p. 10; October 2004.

#### **4. Narrow Field of View (FOV)**

The FOV is the amount of a given scene captured by the camera and is completely dependent upon the type of camera being used aboard the UAV. A narrow FOV provides a much smaller picture than that normally be seen by a human with his or her own eyes and is appropriately described as looking through a soda straw. As the FOV increases, operators obtain greater context of the area of interest, but it becomes more difficult to identify individual targets due to loss of resolution. Cameras with zoom capability allow the mission payload operator (MPO) to change the FOV during mission performance. Other cameras may have the capability to pan and tilt allowing operators to “point” the camera in any direction within the limits of the camera. This functionality gives operators the flexibility of looking in directions not completely determined by the UAV flight path, but pan and tilt do not change the size of the FOV.

#### **5. Unknown Search History**

On most SUAS, the air vehicle operator (AVO) controls the vehicle’s flight path while another operator, the MPO, controls and monitors the optical data returned. While most missions have automated flight paths following a given set of waypoints to direct the UAV, most systems have no automated mechanism to ensure that all areas of interest have been observed. Areas within the camera’s FOV can be obstructed by hills, trees and buildings that block observation of the areas behind it.

### **B. POOR INTEROPERABILITY**

A simple definition was put forth by the Committee on Autonomous Vehicles in Support of Naval Operations in their 2005 report to the Navy: Systems are interoperable if users can easily and confidently make them work together in reasonable combinations that have never been tried before. A counter example of this occurred during set up for the field experiment which will be described in Chapter VIII. The experiment called for receiving live video data from two Naval Postgraduate School (NPS) designed SUAVs. When difficulty was encountered getting one of the vehicles airborne, operators attempted to receive data from a different SUAS called Raven. It was quickly discovered that the data format used by the Raven was incompatible with the application program being used for the experiment and therefore the Raven’s video feed could not be used.

Interoperability difficulties such as this will rise with the growing number of UAS in use throughout DoD, the civilian community at large and our allies around the world. Most of the UAS in development today are being designed as stand alone units. Airframes, autopilots, communication, payload processing, and integration with the larger command and control structures are being designed on a case by case basis with little attention devoted to ensuring they are designed with Joint/Combined interoperability requirements in mind. With each different UAS that participates in a military operation, it becomes harder to manage and coordinate air combat operations because each system will have its own unique software and MCS.

### **C. OPERATIONAL SUPPORT**

Operational support is a broad area that can not (and should not) be neglected when designing UAS. Operational support considers the requirements for manpower, training and logistics throughout the lifecycle of the UAS. In most DoD acquisitions, operational support costs easily top those of other categories such as research and development, procurement and construction costs. Some estimates place operations and support costs between 70 to 80 percent of the total life cycle costs of an acquisition system.<sup>14</sup> This challenge can be mitigated upfront by considering these issues during UAS design and development.

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<sup>14</sup> Article from Defense AT&L Magazine by, Cosmo Calobrisi entitled Meaningful Metrics for Total Life Cycle Costs, May-June 2006 issue.

## **IV. TECHNICAL REQUIREMENTS FOR MISSION SUCCESS**

### **A. INTRODUCTION**

The military, government agencies and commercial companies are spending millions of dollars to rigorously explore the best capabilities and/or systems to pursue. A good systems engineering approach is needed to help integrate these developments with other capabilities and systems that will lead to the best value for the organization and ultimately the taxpayers. The current expectation assumes best value will result in recommendations that encourage modular designs which will enable plug-and-play functionality between components. Additionally, this design should fit well within the larger context the Global Information Grid to enable net-centric warfare.

This chapter will outline the primary missions performed by UAS today and those missions that are expected to be performed in the near future. The technical functions required to allow these missions to be successful will be discussed and a mission-versus-function matrix is presented to show what functions are, or will be, required for specific UAS missions. The matrix will form the cornerstone on which to design a FMCSS.

The primary missions that UAS currently perform are those involving ISR. These missions have proven their value to battlefield commanders by providing enhanced detection, identification, tracking, and reconnaissance of contacts in an AOI. Depending upon the specific system, UAS are capable of searching, collecting, locating, processing, updating, and delivering data to decision makers at all levels within the command and control structure with the goal of improving situational awareness (SA). SUAS are less capable than larger systems due to limited payload capacity and smaller processing power, but in general, employment of all UAS share the following objectives:

- a. Maximize sensor coverage
- b. Maximize likelihood of detecting targets of interest
- c. Minimize the time between detection and identification
- d. Minimize uncertainty regarding target location and movement
- e. Minimize time latency between UAS data collection and incorporation into SA
- f. Maximize collection of priority intelligence requirements

UAS are well suited to provide the capabilities needed to perform ISR missions where manned aircraft were once required. They can conduct the so-called “dull, dirty and dangerous missions” when limited numbers of manned assets are available or when circumstances present unacceptable levels of risk to personnel. For example, UAS are finding increasing roles in the area of border security where it is desirable to limit demands on aircrews and more expensive manned aircraft. In hostile environments with high threat due to shoulder launched weapons, SUAS are a viable replacement for manned helicopters due to their minimal radar cross-section and insignificant heat signature. UAS offer an alternative to ground commanders with force protection missions by employing a UAS in place of ground combat patrols to provide early warning of possible threats. UAS can provide battle damage assessment information that would otherwise require manned aircraft or satellite resources. In a maritime environment UAS can provide surveillance of vessels being boarded during maritime interdiction operations (MIO).

## **B. TECHNICAL REQUIREMENTS**

Given the overwhelming priority placed on the STAR mission, this section will discuss the technical requirements needed of SUAS in order to effectively accomplish STAR missions.

### **1. Visual Display**

The visual display is the primary means of receiving information about the environment in which the SUAS operates. Key parameters associated with visual display are: Time to detect target, image stability, field of view (FOV), target geo-location and search history. These parameters will be discussed in the following section.

Figure 9 is a representation of the time available to the MPO to detect a target from the visual scene as a function of altitude and speed.



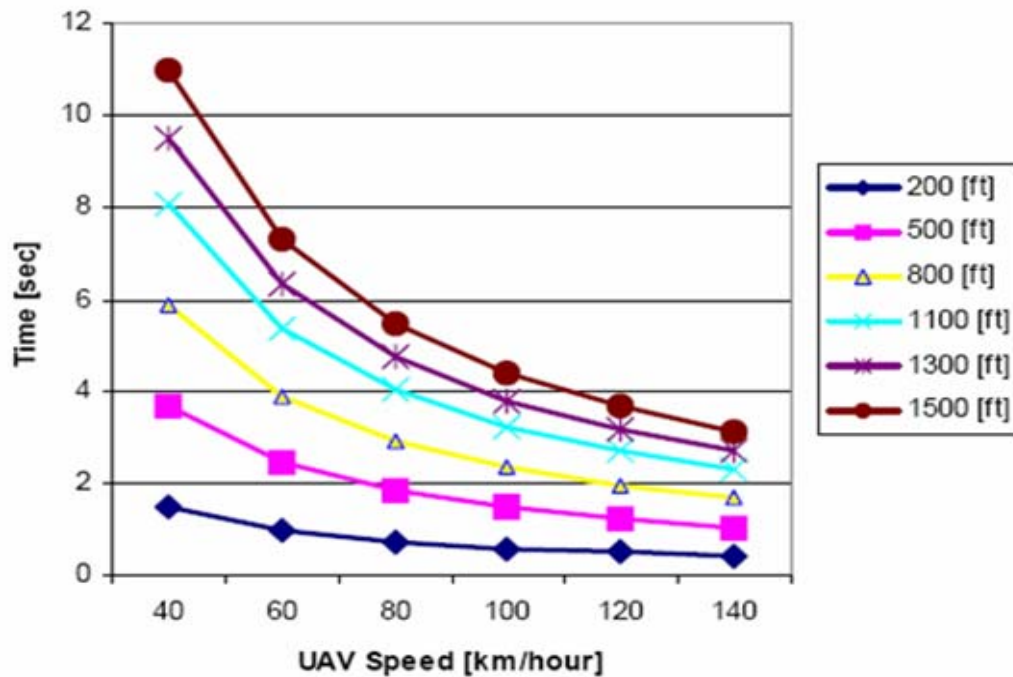


Figure 9. Time of available to detect a target (From: Human Systems Integration and Automation Issues in Small Unmanned Air Vehicles; Michael E. McCauley, Panagiotis Matsangas; p. 9; October 2004)

The assumptions underlying the model are:

- The UAV is flying at constant speed over ground (in [km/hour]) and height (in [ft]). Typical air speed for existing SUAVs is in the 80 to 100 km/hr range.
- The camera is stabilized.
- The target is stationary.
- There are no lags, or other errors.
- The FOV (30°) of the camera corresponds to a typical value found in existing SUAS.

It can be seen that higher altitudes and slower speeds provide the operator more time to detect a target. Only altitudes over 500 feet will provide greater than 2.8 seconds to recognize a target.

**a. Time to Detect Target**

In this sense we take into account the time an operator, presumably the MPO, takes to identify a possible target from an EO/IR feed originating from a SUAS.

For STAR missions, until a target is identified, the only intelligence gathered is that no target exists within the area of interest. In some cases this is the desired state and no further follow on action is required. However, for most missions including strike, EA, or CSAR, a target should be identified quickly in order that the next phase of the mission may commence. Target identification is required in virtually every UAS mission with the exception of the communications relay mission.

In Chapter III experimental results showed that it took approximately 2.8 seconds to detect a target in a natural scene photograph. The experiment made assumptions that will not always hold true for real world missions such as stabilized cameras and stationary and unobstructed targets. It would be interesting to know how long it takes, on average, to detect real targets in dynamic environments with varying degrees of cover and concealment and with differing camera capabilities. This is an area that deserves future research that could guide designers in choosing the optimal sensor for a given mission under various operational environments.

From a command and control ( $C^2$ ) perspective, as target information is passed up the chain of command and distributed to friendly units throughout the AOR, they are empowered with greater SA. Their enhanced SA gives decision makers a  $C^2$  advantage over potential adversaries and leads to faster and better decisions. The time required to collect and deliver this information up the chain of command is inversely proportional to mission effectiveness. The quicker a target can be identified, the faster the next phase of the mission can begin, thereby denying adversaries time they would otherwise have to thwart friendly plans.

Examples of important information that can be collected from SUAS equipped with EO/IR sensors includes:

- Target Location (within context of visual display)
- Target Activity
- Target Size
- Target movement

***b. Target Geo-location***

Target geo-location was identified as a desired capability for three missions in Table 6. The effectiveness of STAR, Strike/SEAD, and CSAR all depend, to some extent, on the ability of the UAS to geo-locate a target of interest. STAR missions should provide target coordinates of enemy units which are then fed to friendly forces who utilize this information to carry out a strike mission. Obviously these strike missions require very accurate target positioning lest a GPS guided weapon, such as JDAM, could miss its intended target resulting in fratricide or collateral damage.

***c. Image Stability***

Image stabilization is a problem with SUAS due to the “bounce” encountered with air turbulence. If a zoom lens is used, image stability gets worse when zooming on an area or target of interest. Additionally, for cameras equipped with pan and/or tilt capability, the MPO will attempt to keep the target within line-of-sight (LOS) as the target moves and this usually results in further video display oscillations.

Ideally, a camera will stay focused on a potential target and remain immune to UAV fluctuations. For most SUAS, such as the prolific RQ-11 Raven currently used in Iraq and Afghanistan, the sensor payload (EO and IR cameras) is an integral part of the airframe and can not be moved. This design contains no form of mechanical stability making the returned images completely susceptible to aircraft “bounce.” For other SUAS with gimballed cameras providing pan and tilt capability, payload restrictions make it difficult to incorporate more massive inertially stabilized systems that are found on larger UAS. A possible solution to the SUAS image stability problem involves using software in lieu of hardware. Software algorithms that can be integrated within existing SUAS, at the vehicle or GCS level, may be a potential solution to reduce the instability of images viewed by operators.

***c. Enhanced Field of View (FOV)***

As mentioned in Chapter II, the FOV is the amount of a given scene captured by the camera and is completely dependent upon the type of camera being used aboard the UAV. For UAS equipped with cameras having zoom capability, MPOs can change the FOV provided. STAR missions orient on the location or movement of the reconnaissance objective. Objectives may be stationary such as terrain features or a

general locality, or a mobile enemy force. Often when reconnoitering, the MPO will see a potential target and need to “zoom-in” (increase zoom angle) to gain better a look. As the operator “zooms-in,” target resolution will increase, but FOV will decrease. This smaller FOV removes context that was previously available when using a smaller zoom angle. The smaller FOV also makes the visual display appear to be shakier and less stable as discussed above. A capability that provides context while providing resolution is needed to enhance UAS mission effectiveness.

#### ***d. Search History***

During field experiments at Camp Roberts, a great deal of coordination between the AVO and MPO was required to perform missions involving target recognition. If the MPO thought he saw something important, he would inform the AVO who would take manual control of the UAV in order to get a “better look.” It was observed that the operators often had difficulty finding the location of interest and determining what areas had previously been searched. A technology that permits instant video replay of areas previously surveyed could significantly improve operator performance and mission effectiveness. Ideally, this capability should be available to the MPO and AVO in real time. Interesting images could be saved locally and sent later to other consumers. It may also be possible to use saved imagery to update terrain databases or a digital map based common operational picture (COP).

## **2. Interoperability**

Besides the technical requirements described above for STAR mission success, it is also important that UAS developers to consider how their designs impact other systems and how well they can interoperate with these other systems. In 2003 the National Defense Industrial Association (NDIA) C4ISR Division together with major UAS industry leaders including Boeing, General Atomics Aeronautical Systems, Lockheed Martin, Northrop Grumman and Raytheon completed a study that addressed common and standard UAS “plug-and-play architectures” that would allow multiple unmanned aircraft, sensors, and mission control ground stations to work in a common network. The study said it had “not found anyone in the UAV industry who is moving toward architecture commonality.”<sup>15</sup> It called for DoD to enforce compliance with common

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<sup>15</sup> *UAV Programs Need Common Standards, Says Industry Study*, Sandra I. Erwin, National Defense Magazine, October 2003.

standards and warned that while a universal architecture is achievable, it must be managed properly.

In a July 2004 interview with National Defense Magazine, Dyke Weatherington, the deputy of the UAV planning task force at the Office of the Secretary of Defense, acknowledged that "...in the next two or three years, you'll see some air vehicle interfaces...and the focus should be on defining a standard air vehicle interface for small UAVs because of the ease of receiving data from them, the large number of potential users and the airspace issues that could arise from hordes of organic squad-level UAVs."<sup>16</sup> He noted that different classes (i.e. sizes) of UAVs would have similar, but not identical interfaces. SUAS, for example, would not likely carry weapons and therefore not be in need of a weapons interface. Additionally, he envisioned that interfaces for the SUAS would be designed to work on control stations such as laptops and PDAs likely to be found at the small unit level. This prediction is slowly becoming a reality as many of the new SUAS being developed utilize laptop computers or handheld PDA-like devices to control the UAV and payload.

At the international level, UAS are currently produced by 14 of the 26 member states of NATO. This fact further underscores the importance of conforming to standards in order to optimize battlefield effectiveness in ever increasing multi-national operations. Recognizing the importance of interoperability, NATO has written Standard Agreement (STANAG) 4856 to address standard interfaces of UAS control systems. In its second edition, STANAG 4586 was conceptualized to promote interoperability between UAS to include one or more GCS, UAVs and their payloads, and the Command, Control, Communication, Computer and Intelligence (C4I) network, particularly in joint operational settings.<sup>17</sup> In an effort to align itself with this standard, The U.S. Navy has been developing the Tactical Control System (TCS) in order to provide a single product for the control of UAVs from the different manufacturers. The Army has developed its own common GCS called the One System station for use with Shadow, Hunter and Predator UAS which will also be compliant with STANAG 4856. The Marine Corps and

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<sup>16</sup> *Pentagon Setting Guidelines For Aircraft Interoperability*, Michael Peck, National Defense Magazine, July 2004.

<sup>17</sup> *Human Performance considerations in the Development of Interoperability Standards for UAV Interfaces*, M.L. Cummings, J.T. Platts, A. Sulmistras, 2006.

Air Force are conducting bi-monthly meetings with their Army-Navy counterparts to ensure their UAS procurements are interoperable with those of the Army and Navy and therefore compliant with the NATO standard.

### **3. Operational Support**

#### ***a. Manpower***

Currently, UAS crews consist of operators based on the functional areas they control such as mission payload operator (MPO), air vehicle operator (AVO), communications officer, weapons release authority (for Unmanned Combat Aerial Vehicles (UCAVs)), and a mission commander. Applications to reduce these functional manpower positions into fewer positions are just beginning to be considered. Compared to manned aircraft, UAS have the potential to significantly reduce these costs. Savings will be achieved when functional manpower positions are reduced or more UAVs can be adequately controlled by the same positions.

To realize these savings, UAS must become more autonomous, that is, capable of performing functions in flight that are currently performed by human operators at the MCS. A key challenge being addressed is how the operator interacts with the aircraft under normal operations and when an emergency develops. Interfaces must be designed to allow the operator to understand what is going on at a glance so that adequate time is available to handle both normal and emergency situations as they develop.

The Army currently has four different types of UAS to conduct operations: the RQ-11 I-Gnat which was recently upgraded with a turbocharged engine to extend its operating altitude to 30,500 feet, the RQ-5/MQ-5 Hunter and RQ-7 Shadow which are considered tactical UAS (TUAS); and the RQ-11 Raven, a SUAS. To get a quick look at the manpower required to operate these individual systems, a “best case” “human-to-UAV” ratio is calculated by assuming all UAVs are airborne at one time.

- The Hunter has 48 military and 5 contractor personnel to operate six UAVs for a “human-to-UAV” ratio of 8.8:1.
- The Shadow UAS consists of four UAVs with 22 military and 2 contractor personnel giving it a ratio of 6:1.
- The I-Gnat organization is made up entirely of contractor personnel (normally 10) and contains three UAVs for a ratio of 3.3:1.

- Lastly, the Raven SUAS has the best “human-to-UAV” ratio with only two operators and three UAVs for a ratio of only 0.7:1.

Current UAS operations however, normally do not involve all aircraft in the system to be flying simultaneously. Despite having the capability to operate multiple UAVs per system simultaneously, the limited number of communication frequencies available often restricts the number to one UAV airborne at a time. Assuming only one UAV is flying at any given time yields “worst case” ratios of 53:1, 24:1, 10:1 and 2:1 for Hunter, Shadow, I-Gnat and Raven respectively.

***b. Training***

Most DoD UAS operating today employ contractors to conduct the majority of their UAS training requirements. This can be attributed to the fast pace at which UAS are being developed and underscores the lack of interoperability among the wide variety of UAS in the field. Until unmanned aviation becomes standardized within the services, the use of civilian contracted trainers will need to continue. For those UAS that require unique and costly maintenance, the use of contractors may prove a better option than training military personnel. The status of training for the individual U.S. military services is provided in the 2005 Roadmap and reproduced in Table 5 below. With the exception of the Army's Hunter and Shadow training programs, each UAS has a dedicated training program with the students in these courses ranging from experienced rated officers as pilots to recent enlistees as airframe maintainers.

System/Course	Service	Location	Duration	Throughput	Flt Hours	Staff
<b>Global Hawk</b>	Air Force	Beale AFB, CA				10
Pilot			26 weeks	48/yr	32	
Sensor Operator			12 weeks	18/yr	48	
Maintenance			5 weeks	77/yr*		
<b>Hunter</b>	Army	Ft Huachuca, AZ				300**
Internal Pilot			24 weeks	40/yr	21.5	
External Pilot			16 weeks	4/yr	30	
Maintenance			10 weeks	20/yr		
Technician			11 weeks	20/yr		
<b>Pioneer</b>	Navy	OLF Choctaw, FL				37*****
Mission Commander			3 weeks	17/yr	10	
External Pilot			17 weeks	24/yr	102***	
Internal Pilot/Payload Operator			14 weeks	40/yr	56	
Mechanical Maintenance			7 weeks	18/yr		
Technical Maintenance			9 Weeks	24/yr		
<b>Predator</b>	Air Force	Indian Springs AFAF, NV				22
Pilot			13 weeks	48/yr	38	
Sensor Operator			14 weeks	48/yr	37.5	
Maintenance			4 weeks	95/yr*****		
<b>Shadow</b>	Army	Ft Huachuca, AZ				300**
Operator			24 weeks	240/yr	14.5	
Maintenance			8 weeks	40/yr		
Technician			9 weeks	40/yr		
*Number of graduates is total from the seven Global Hawk Maintenance courses. Duration is average length of the seven courses. **Total staff supporting Hunter and Shadow instruction at the U.S. Army UAS Training Center. ***Consists of some 80 hours flying subscale RC models plus 22 hours flying the Pioneer. **** Number of graduates is total from the five Predator Maintenance courses. Duration is average length of the five courses. *****Total staff supporting Pioneer training at OLF Choctaw.						

Table 5. Status of Training (From: UAS Roadmap, 2005)

*c. Identified Training Challenges*

The 2005 Roadmap has identified four distinct training issues and goals to be pursued:<sup>18</sup>

- Although a spiral acquisition approach is favored for most UAS programs, it imposes an unrecognized burden for UAS trainers: always being one or more steps out of phase with the capabilities being incrementally fielded. This requires additional training (i.e., cost) at the unit level after the student completes initial training.
- Current ground stations are not designed to be dual capable for use in both controlling actual missions and conducting simulated flights for training.

<sup>18</sup> Unmanned Aircraft Systems Roadmap 2005-2030, 4 August 2005, Office of the Secretary of Defense, pp. 63-64.



This drives added product support costs for dedicated simulators and task trainers by requiring more numerous and higher fidelity simulators and trainers.

- The current and projected OPTEMPO associated with the Global War On Terrorism (GWOT) does not allow systems to be taken off-line for extended periods of time in order to implement hardware and software improvements and to train operators on the new capabilities.
- Most UAS maintenance training lacks dedicated maintenance trainers as well as digital technical orders and manuals with embedded refresher training. This results in factory representatives having to be fielded at most UAS operating sites and to deploy to war zones to compensate for inadequate training.

#### **E. FUNCTIONS-VS- MISSIONS**

This chapter is concluded with a table showing UAS missions versus the functions or capabilities required to successfully accomplish the mission. The table has an additional column that identifies the particular UAS subsystem associated with the given function and will be elaborated on in Chapter VII. For now, the intent of Table 6 is to provide designers a list of the functional capabilities needed to effectively perform the most likely missions that current and future UAS will conduct.

SUBSYSTEM	DESIRED FUNCTIONS/CAPABILITY	MISSIONS				
		STAR	EA	STRIKE SEAD/ DEAD	NETWORK NODE/ COMMUNICATIONS RELAY	CSAR
Vehicle	Propulsion	X	X	X	X	X
Vehicle	Electrical Power	X	X	X	X	X
Vehicle	Vehicle Systems Monitor	X	X	X	X	X
Vehicle	Vehicle Control And Stabilization	X	X	X	X	X
Vehicle	Autopilot / Homing	X	X	X	X	X
Sensor/Weapon	Sensor Measurement And Control	X	X	X		X
Sensor/Weapon	Weapon Measurement And Control			X		
MCS	Fly-The-Sensor	X	X	X	X	X
MCS	Communications Link Monitor	X	X	X	X	X
MCS	Operator / Flight Control	X	X	X	X	X
MCS	Flight Pattern Execution	X	X	X	X	X
MCS	De-Confliction	X	X	X	X	X
MCS	Battlefield SA Update	X	X	X	X	X
MCS	Tactical Mission Planning	X	X	X	X	X
MCS	Multi-UAV Coordination	X	X	X	X	X
MCS	Sensor Commands	X	X	X		X
MCS	Flight And Airspace Planning	X		X	X	X
MCS	Known Search History	X	X	X		X
MCS	Commander'S Intent	X	X	X		X
MCS	Rehearsal	X	X	X		X
MCS	Image Stabilization	X		X		X
MCS	Target Geo-Location	X		X		X
MCS	Multiple Target Tracking	X	X			X
MCS	After Action Report (AAR)		X	X		X
MCS	Target Assignment	X	X	X		
MCS	Strategic Mission Planning	X			X	
MCS	Real Time Video Target Tracking	X		X		
MCS	ROE			X		
Communication	Flight Control Link UAV to GCS	X	X	X	X	X
Communication	Sensor Control Link UAV to GCS	X	X	X	X	X
Communication	Link Between GCS and MCS	X	X	X	X	X
Communication	Link Between MCS and Other Consumers	X	X	X	X	X
Support	UAS Storage	X	X	X	X	X
Support	Deployment / Delivery	X	X	X	X	X
Support	Maintenance	X	X	X	X	X
Support	Logistics Re-Supply	X	X	X	X	X

Table 6. Functions vs. Missions

## V. GENERIC UAS SYSTEM DESIGN

### A. INTRODUCTION

A large number of UAS are being developed and much of this development is driven by economic considerations. Governments, and particularly their militaries, understand the cost savings they can realize by implementing UAS systems into areas traditionally held by piloted aircraft. The American Institute of Aeronautics and Astronautics (AIAA) lists hundreds of UAS either under development or in production worldwide as of July 2005. Design of UAS should seek to identify and standardize the functions required to accomplish UAS missions and make the components as interoperable and potentially plug and play compatible as possible. This standardization will lead to more affordable systems without sacrificing capability.

In this chapter the basic concept and design of a generic UAS is discussed. For practical purposes, there is little difference between this generic model and that of a SUAS and therefore the model applies equally to both.

### B. BASIC CONCEPT OF AN UAS

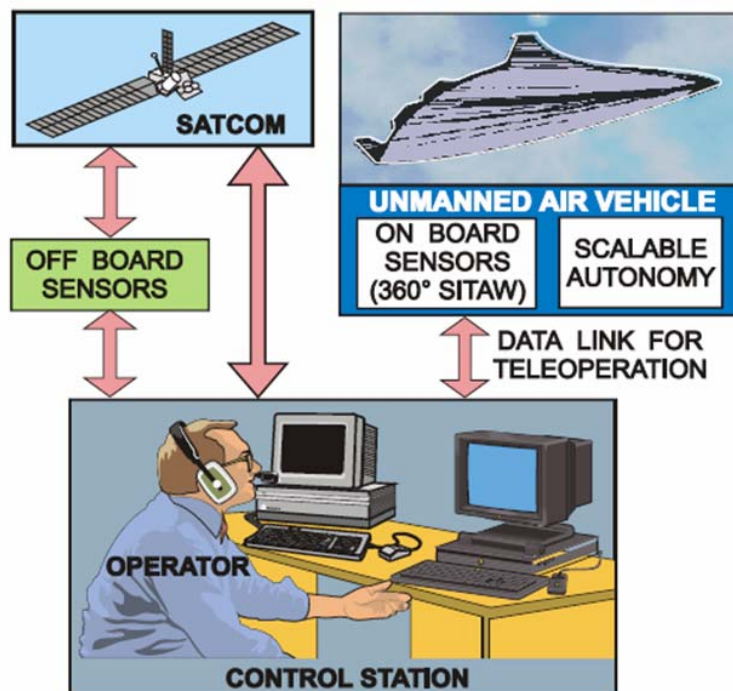


Figure 10. UAS Concept (From: Fundamental “UAV” Concepts and Technological Issues, Uwe K. Krogmann, North Atlantic Treaty Organisation, Research And Technology Organisation, RTO-EN-025 AC/323(SCI-109)TP/41)

Figure 10 on the previous page illustrates the basic concept of an UAS. Although the aircraft is unmanned, the system is not. Human operation is central to the flexible control of every UAS. If properly equipped, the operator can exploit information not only from onboard UAV sensors, but also information from offboard sensors such as other UAS or ground units or even information from databases inside and outside the AOR. The control station could be located anywhere, i.e., on the ground, at sea, or in the air or space. The important goal of modern UAS is to put an operator's brain in the cockpit while leaving his/her body on the ground. With this human in the loop (HIL) operation, the UAS contains the rational, judgmental, and moral qualities of a person and enables the system to be operated over a diverse and dynamic set of conditions and missions.

### **C. UAS FUNCTIONAL SUBSYSTEMS**

The UAS, and indeed all systems, consist of subsystems that are assembled together in such a way that they are capable of performing functions that the individual subsystems would be unable to accomplish alone. Subsystems are individual and distinct units within the system capable of performing their own unique functions. These subsystems consist of components that may be located close together or far apart. Regardless of their location, the designer must integrate these subsystems and components into a complete system, the UAS, that enables an aircraft with its onboard sensors and offboard MCS to perform a wide range of missions without the physical presence of a pilot in the aircraft.

In broad terms, a typical UAS can be broken down into five major functional subsystems as shown in Figure 11. These subsystems provide all the functional capabilities for the UAS that were listed in Table 6. Some of the functions are performed within multiple subsystems and, therefore, no perfect one-to-one correlation between functions and subsystems exists. The table, however, provides a point of reference to enable understanding of where in a typical UAS these functions reside. This section provides a brief description of the subsystems and the functions they provide.

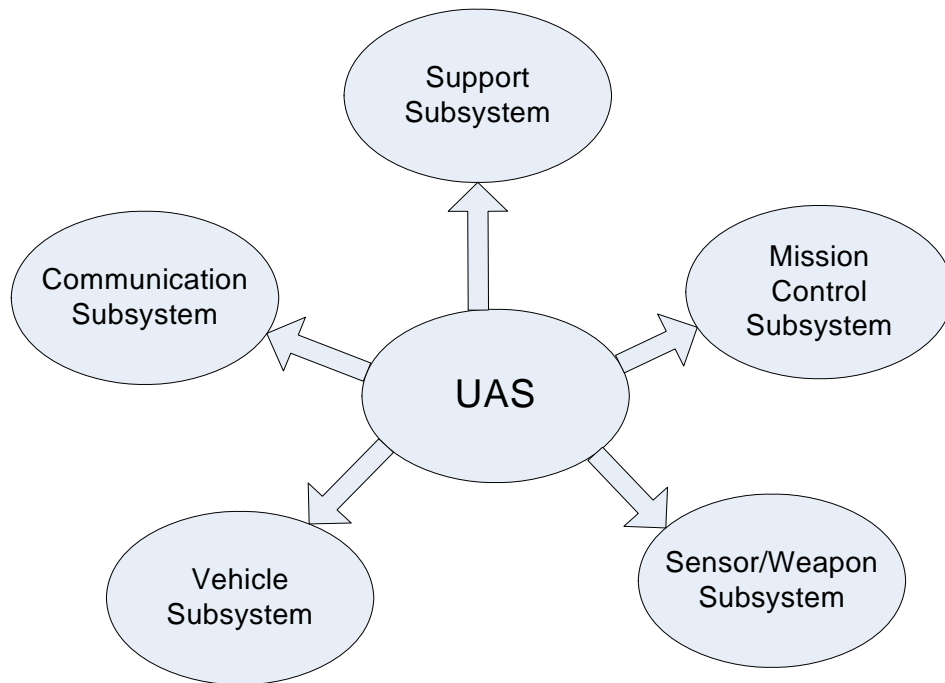


Figure 11. UAS Functional Subsystems

### 1. Vehicle Subsystem

The vehicle subsystem consists of the aircraft and the components related to its management and control. Major components within the vehicle subsystem could include the engine, alternator (generator), landing/takeoff gear, autopilot, avionics, etc. The vehicle subsystem provides the following functionality listed in Table 7:

Propulsion	Vehicle Control and Stabilization
Electrical Power	Auto-reflex / Stabilization
Vehicle Systems Monitor	Autopilot / Homing

Table 7. Vehicle Subsystem Functionality

### 2. Mission Control Station Subsystem

The mission control station (MCS) is a generic term used to describe the people and components involved with mission planning and flight control. The MCS often consists of two parts, one located close to UAV operations which is referred to as the ground control station (GCS), and another station that handles the higher level mission planning and battlespace awareness issues such as a theater level command and control

headquarters or a smaller tactical operations center (TOC). For simplicity, we refer to either component as the MCS. Most of the functional capability of an UAS resides in the MCS subsystem. Table 6 lists 21 unique functions performed within this subsystem. Conceptually, the MCS subsystem contains the “brains” of every mission and provides for the command and control (C<sup>2</sup>). The MCS subsystem could be physically located on the ground, at sea, or in the air. It could also consist of more than one station to increase reliability, for example, in a network-centric organization that has multiple MCS networked together. If one station is destroyed or otherwise loses communications with the vehicle, the other MCS would take over where the first left off. Often, some MCS function are delegated to a “lower level” MCS such as a local GCS. The GCS mentioned earlier, is usually responsible for “flying” the UAV and sending data back to a higher level MCS that is responsible for transforming the raw data received into actionable intelligence (information).

Operator / Flight Control	Tactical Mission Planning	Waypoint Command Generation
Real Time Video Target Tracking	Rehearsal	Flight And Airspace Planning
Image Stabilization	Search Pattern Generation	After Action Report
Flight Pattern Execution	Target Id And Location	Communications Link Monitor
Local De-Confliction	Close To Real-Time Tracking	Strategic Mission Planning
Multi-UAV Coordination	Battlefield SA Update	Commander's Intent
Sensor Commands	Fly-The-Sensor	Target Assignment

Table 8. Mission Control Station Subsystem Functionality

### 3. Sensor/Weapon Subsystem

The sensor/weapon subsystem contains the components that sense or effect the environment. This subsystem can be broken into other distinct subsystems as the complexity increases. While somewhat simple when described at high level, the sensor or weapon components themselves can be very complex and constitute a significant fraction of the total UAS cost. The majority of SUAS are unarmed, and predominantly perform STAR missions; therefore, the weapon subsystem is not applicable to SUAS operation. Because the sensor(s) is attached to the air vehicle, operators normally think first in terms of flying the UAV to the AOI. Once the UAV reaches the AOI, efforts are shifted to positioning or aiming the sensor at a potential target. With the target within the sensor’s FOV, the product--video data for example, can be transmitted back to the MCS

and distributed. Common sensors aboard a SUAV include EO/IR cameras and GPS. Functionality of the sensor / weapon subsystem include:

Sensor Measurement And Control
Weapon Measurement And Control

Table 9. Sensor/Weapon Subsystem Functionality

## 5. Communication Subsystem

The communications subsystem consists of components located throughout the UAS and supports communication at any level within the bigger system. For example, part of the communication subsystem provides the video link between a camera and the MPO and consists of the radio transmitter aboard the UAV and the receiver located at the GCS. Another part of the communication subsystem may pass data between a platoon or squad level GCS located near the forward line of troops (FLOT) and a battalion tactical operation center (TOC).

Without the communication subsystem it would be impossible to create the virtual pilot by putting his or her brain in the cockpit as discussed earlier. For SUAS, communication is accomplished through an RF line of site (LOS) link between the aircraft and operators. Larger UAS may have multiple links including satellites that significantly extend the distance between operator and UAV. Problems with the communication subsystem such as loss of link, will usually significantly impact mission performance. If the communication link is lost (worst case) for example, most missions will have to be aborted since the majority of UAS lack the autonomy required to effectively execute important missions without a human-in-the-loop (HIL). Latency is another common communication link problem that may prevent remote operators from controlling the UAV in real time. The latency issue requires local operators within LOS to perform take-off and landing maneuvers that can not tolerate the time delays associated with long communication links such as those involving satellites.

Communication	Flight Control Link UAV to GCS
Communication	Sensor Control Link UAV to GCS
Communication	Link Between GCS and MCS
Communication	Link Between MCS and Other Consumers

Table 10. Communication Subsystem Functionality

## 5. Support Subsystem

As UAS operations continue to grow, they become more dependent upon robust service and support organizations that can remain responsive to their increasing needs. Planning, managing, and executing supply support and maintenance involves synchronized coordination at many levels to ensure seamless integration. Logistics and maintenance should never be overlooked when designing a UAS as most of the total life cycle costs are traceable to these functions. Some of the key functions associated with the support subsystem include:

Uas Storage	Maintenance
Deployment / Delivery	Logistics Re-Supply

Table 11. Support Subsystem Functionality

## D. UAS FUNCTIONAL LAYER MODEL

Another descriptive way to illustrate an UAS is with the aid of a functional layer model as shown in Figure 12. There is no direct one-to-one correspondence between a particular subsystem and a particular functional layer, nor is it necessary to explicitly show each subsystem in the functional layer model. The important concept to convey concerns the direction of data flows and the reaction times associated with the different functional layers within the UAS. Other systems engineering considerations are shown on the right side of the figure. These design characteristics represent the tradeoffs that UAS designers must consider when developing UAS.



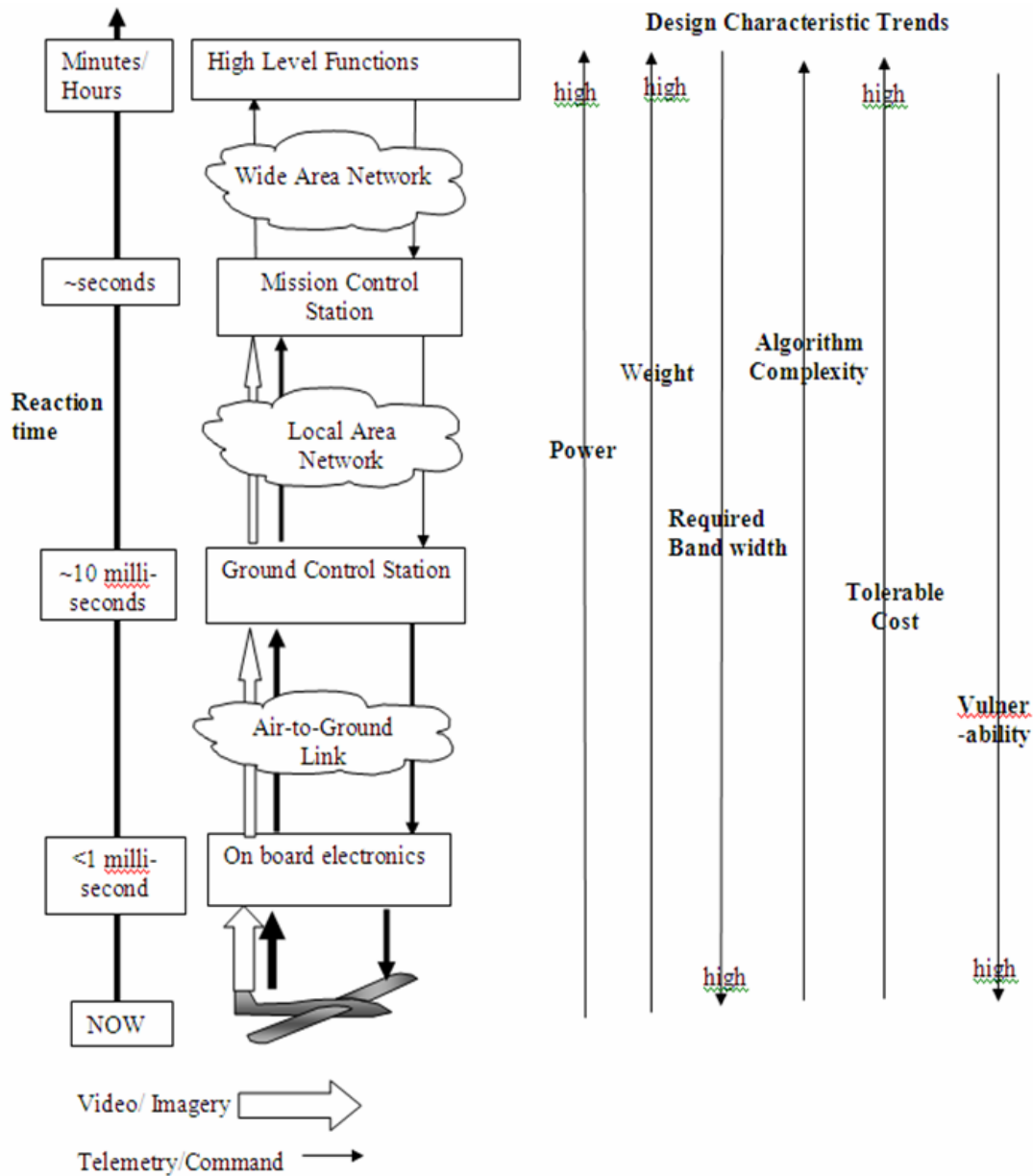


Figure 12. UAS Functional Layer Model

The layers implemented in the functional design model show the division between the low level fast reaction time components required to implement flight control, housekeeping, and sensor maintenance functions traditionally executed by a pilot or navigator, from the higher level functions required to execute mission objectives. Lower level functions are treated as services to higher-level functions and low-level implementation details should be hidden in order to reduce cognitive load on human operators. For example, if a surveillance mission is initiated, the MCS may require a

scan of a road segment and receive the output of a sensor with sufficient resolution and dwell time to allow for vehicle identification. The exact flight path required to point the sensor, provide communication connectivity, and/or monitor fuel consumption should be provided as a service to the MCS by lower level functions either within the UAV or GCS. These services should not be an additional task(s) performed by the MCS.

#### **E. FLY THE SENSOR**

The generic design description presented in this chapter views the UAS as a means to put human eyes on a target of interest without the need for those eyes to be in physical danger i.e., the virtual pilot idea. The design focus centers on the UAV which must be flown into an area of interest in order to get the appropriate sensors fixed on an expected target. Once this is accomplished and sensor data is successfully transmitted back to human operators, the “real mission” can begin. By “real mission” we mean the decision making aspects of missions such as interpreting video from a STAR mission to gain intelligence on an adversary or deciding whether or not to launch a missile in a Strike mission. Decision makers are not particularly interested in how a vehicle gets to the AOI. Tasks such as “driving” the aircraft or monitoring a video screen to discern useful information from noise is a distraction and impediment from accomplishing the more important mission at hand.

The title of this section, “Fly the Sensor,” implies a shift of focus concerning UAS operation. Instead of concentrating on flying a UAV with the pilot safely on the ground, we suggest shifting the mission emphasis to that of flying an appropriate sensor (or effector in the case of a combat UAV (UCAV)). The benefit of designing an UAS with a focus on flying the sensor vice the aircraft, is that more human attention is placed on mission critical information as opposed to the lesser, but still important, aspects of flying the vehicle.

Notice in the design characteristics of Figure 12 that *algorithm complexity* increases as data rises to higher levels in the functional model. Algorithm complexity is equivalent to the cognitive load or processing “horsepower” that is required of the UAS to perform a given task. The algorithm complexity is proportional to task complexity

and, fortunately, also proportional to reaction time. As tasks become more complex, a human would require more thinking, or a computer would require more computing, in order to effectively deal with the task. Performing the higher level functions, such as analyzing video, have naturally been delegated to human operators since human operators excel over computers when it comes to image understanding. However, at the lower functional levels in the model, the tasks and algorithm complexity become simpler and the reaction time required gets compressed. At this point machines become better than humans, in terms of speed and accuracy, and these tasks are better relegated to computers and software.

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## **VI. TECHNOLOGY GAPS**

### **A. INTRODUCTION**

While UAS performance has grown by leaps and bounds over the last 20 years, there remain a virtually unlimited number of areas where improvements can be made. This is particularly true for SUAS since they have been in operation for a shorter period of time. It would be impractical (and probably impossible) to address all the technology gaps being confronted by developers of SUAS in one volume. This chapter will address several technology gaps associated with the display of visual data returned from SUAV EO sensors (cameras).

### **B. TARGET GEO-LOCATION**

The ability to rapidly detect and identify potential targets, both fixed and mobile, from UAS sensor feeds is a critical function in several mission areas. Simple geo-location techniques are sufficient for general orientation but are not suitable for providing accurate sub-meter targeting coordinates. Historically, military target planners relied on comparisons between hard copy reference photos and tactical images derived from battlefield aerial reconnaissance photo sources. The advent of digital photography and near real-time (NRT) transmission of imagery has shortened the time needed to observe an AOI, but the problem of NRT geo-location remains a significant problem particularly for SUAS. To illustrate a fundamental problem associated with target geo-location, consider a target located on flat terrain as shown in Figure 13. Assuming the platform sensor's coordinates are provided by GPS, and the camera attitude is known from onboard sensors, the angle to the target (pointing angle) can be readily determined. With this information the target coordinates can be approximated quickly by simple trigonometric calculation. Unfortunately, most terrain is not flat and large inaccuracies will result even if the platform location and pointing angle is known.

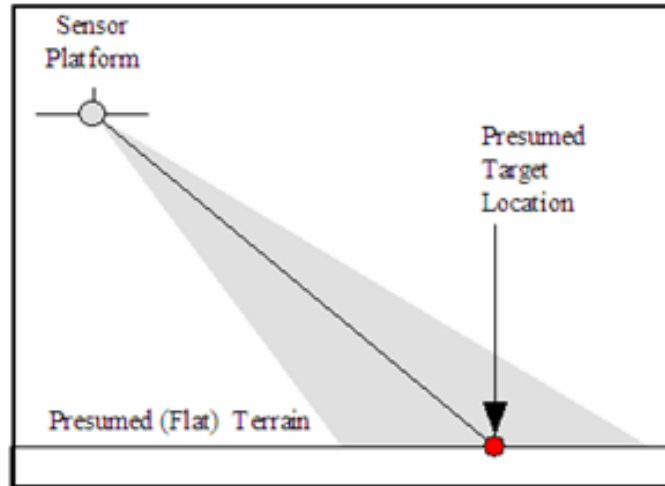


Figure 13. Target On Flat Terrain (From: [www.cardiofix.com](http://www.cardiofix.com); accessed 28 July 2006)

Figure 14 illustrates the error that can result if the terrain is not flat. This error is amplified when the pointing angle increases, for example, when the UAV flies at lower altitude (Figure 15 next page).

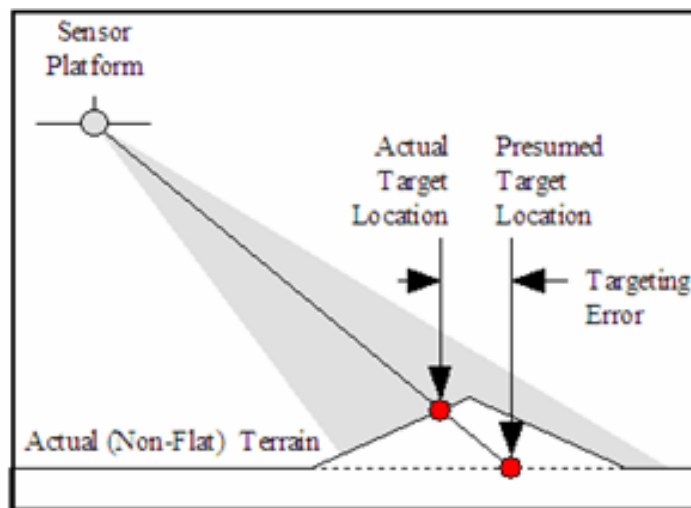


Figure 14. Target On Uneven Terrain (From: [www.cardiofix.com](http://www.cardiofix.com); accessed 28 July 2006)

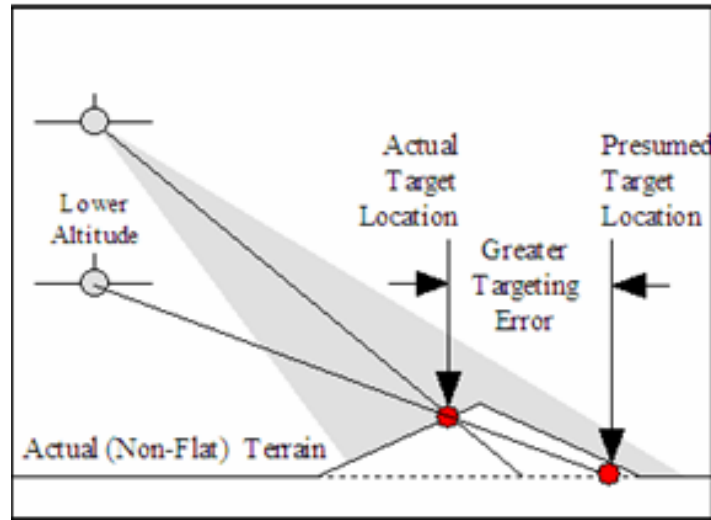


Figure 15. Error At Lower Altitude (From: [www.cardiofix.com](http://www.cardiofix.com); accessed 28 July 2006)

Three key parameters are required to calculate the coordinates of a potential target: 1. Known sensor location at time image was captured; 2. Sensor pointing angle and 3. Sufficiently detailed 3D terrain model. Additionally, accurate time stamps are needed when the image is captured to synchronize the data. Even when these parameters are known, enormous amounts of computation is required to geo-locate the target of interest. NRT target geo-location can not currently be accomplished aboard the UAV due to weight and power constraints, and therefore must be accomplished at the GCS or MCS. The next chapter will describe a unique technology development being pursued at Naval Postgraduate School as a possible new technology solution to the target geo-location problem.

### C. IMAGE STABILITY

Video signals transmitted to the MCS from UAVs are often unstable. As noted in Chapter III, video displayed from a SUAV on the GCS monitor at Camp Roberts was observed to “bounce” on and off the screen approximately two to four times per second. These oscillations were the result of the SUAV being buffeted by the wind due to its small size and mass. For cameras equipped with zoom capability, the image stability problem is worsened when the sensor’s FOV is decreased by zooming in on an area of interest.

Without steady video, image sharpness declines and it becomes harder for an operator to discern finer details. An operator tasked with watching video can remain more alert since eye strain and overall fatigue is reduced when viewing stable video. The possibility also exists to lower the quantity of data (bits) transmitted because steady video will compress better than shaky video. Less data means a smaller storage device is required to capture the same video, or more recording time will result with the same storage device.

At the time of this writing, only one of the 12 different small or mini UAS listed in the 2005 UAS Roadmap came equipped with some form of video stabilization. The Boeing Corporation's ScanEagle SUAS utilized an inertially stabilized gimbaled camera as standard equipment to provide video stabilization. During a recent technology symposium at the Naval Postgraduate School, the author observed a recording of ScanEagle video while operating in wind gusts exceeding 30 mph winds and noted few oscillations in the displayed video. However, inertial stabilization comes with the unwanted costs of added weight and increased power requirements. Alternative image processing technologies using new software could be applied to the video stream at the GCS. Though several electronic image stabilization systems are available, their general use and effectiveness to SUAS has been limited. To enhance video image stability, more robust image processing or ultra light weight inertial gimbaled camera systems, or a combination of these techniques, needs to be developed.

#### **D. SIMULTANEOUS WHAT AND WHERE VIDEO PRESENTATION**

For SUAS, EO cameras are the predominant means for providing video data to the MCS, usually on a fixed monitor. Since the pilot is not seated in the vehicle, vestibular feedback received from changes in vehicle attitude i.e., rotations, will not be felt. Other sensory cues such as audio or proprioceptive information from the muscles in the neck and eyes which aids pilots with viewing direction are also missing. Without these kinesthetic sensory cues, limitations on the operator's situational awareness exist. These shortcomings can result in degraded operator performance such as losing track of a target, difficulties assessing camera, platform, and target motions, confusion in flying



direction of the platform, confusion on viewing direction of the camera, disorientation, and degraded situational awareness.<sup>19</sup>

The current state of UAS automation requires HIL operation and key decisions will often have to be made by human operators. As long as humans remain central to UAS operation, there will always be human factors that must be considered in the system design. A recent study was performed that revealed eighteen human factors issues unique to UAS that deserve future research.<sup>20</sup> Five of the factors are related to the perceptual and cognitive aspects of the pilot interface and research is recommended to study the affects of providing an “augmented reality” or “synthetic vision.”

A separate study by Van Erp and Van Breda has identified at least eight shortcomings concerning remote camera control of unmanned vehicles. One of these shortcomings addressed in the Problem Definition chapter concerns the field of view (FOV). As the FOV gets smaller, the operator may observe better resolution but this comes at the expense of lost context in the area of operation. In other words, the operator may know more about *what* he or she is seeing (due to better resolution), but will know less about *where* they are looking to do decreased FOV. The capability to simultaneously display what the sensor is pointing at while providing context about where the sensor is located is a technology gap existing in most SUAS.

## **E. BANDWIDTH LIMITATIONS**

While technically not the same as data throughput, bandwidth (BW) is the term generally used to describe the data throughput of a communications system. As the BW increases, so does the data throughput. In broad terms, BW limitations can be created by anything that hampers or minimizes that the transmission of data from UAV to the MCS. The communications subsystem discussed earlier is responsible for providing the critical link between the vehicle sensors and the operators located at the MCS. The current paradigm for SUAS operation, and even for their larger counterparts, is to relay nearly all

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<sup>19</sup> Van Erp, J.B.F. & Breda, L. van (1999). Human factors issues and advanced interface design in maritime Unmanned Aerial Vehicles: a project overview 1995-1998. TNO-TM 1999 A004. Soesterberg, The Netherlands: TNO-HFRI.

<sup>20</sup> Human Factors Implications of UAVs in the National Airspace, Jason S. McCarley & Christopher D. Wickens, April 2005.

sensor data back to the MCS for processing. The amount of raw data collected by onboard sensors easily exceeds the onboard processing power of SUAS. To convert this data to useful intelligence, the communications subsystem must transmit this data to the MCS for processing. When doing so, they frequently overwhelm the available communications BW. This section considers several limitations associated with the BW of SUAS.

### **1. Power Limitations**

The communications subsystem is constrained by the power output of the onboard transmitter and the gain of the transmitting antenna. The output power must be sufficient to overcome any losses that could be encountered while transmitting data from the UAV to the MCS. Most SUAS employ omni-directional antennas that radiate radio waves equally in all directions similar to the way the sun radiates light into space. Since the signal is uniform strength in all directions there is no need to worry about directing the antenna, but this method is not very power efficient. Radio frequency power decreases with distance squared. For example, if the MCS is to receive a signal of a given strength from a UAV which moves twice as far away, the onboard transmitter would need to produce four times the power.

To improve performance, the UAS could radiate at higher power or the GCS could employ a directional antenna with a tracking capability to maximize the power received from the UAV. The latter technique is employed by the NPS SUAS. By following the UAV flight path with a high gain directional antenna, the GCS is able to receive a greater amount of the signal being transmitted from the SUAV. The former technique could also be used to improve signal reception from longer distances. Of course the disadvantages of this method are seen as increased size and weight of the UAV transmitter. Most SUAS, and all hand launched systems have payload capacities well under 10 pounds<sup>21</sup>. Additionally, most hand-launched UAV uses batteries to provide for all power requirements including propulsion. To get more power, the UAV would have to carry a larger battery which means more weight, which means less

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<sup>21</sup> The 2005 UAS Roadmap lists eight out of nine SUAS with payloads less than 10 pounds.

endurance. These tradeoffs must be considered to optimize the performance for any particular UAS mission.

## **2. Vulnerability of Active Transmitter**

When an omni-directional antenna radiates, no mechanism is in place to direct the signal energy, hence anyone with a suitable receiver can detect its transmission. Given the large amounts of data collected, particularly from imagery collection associated with STAR missions, the transmitter often appears to be continuously transmitting. This situation makes the transmitting UAV more vulnerable to detection and attack since an adversary will have more time to locate its position. To mitigate this vulnerability, transmitted data can be compressed to reduce the required BW. The downside of this technique is that compression algorithms intentionally discard information that could be valuable. Until onboard processing power increases enough to minimize transmission requirements, compression algorithms will remain one of the better solutions to fill this gap.

## **3. Line-of-Sight Limit**

High altitude UAS can maintain high bandwidth communication links over great distances with other UAVs or the MCS due to their large line-of-sight (LOS) distance. SUAS normally fly at altitudes of less than 1000 feet and have maximum RF LOS of approximately 70 km (Figure 7 Radio LOS vs. Altitude). This coverage assumes ideal conditions with no obstructions between UAV and MCS and high enough transmission power to complete the radio link. For low altitude SUAS flying in urban areas with buildings or in areas with hills, a LOS data link can easily become obstructed. Additionally, discussion with SUAV operators revealed that more typical operating ranges are between 3 and 10 nautical miles due to transmission power limitations.

The terrain encountered during field experiments at Camp Roberts is characterized by many low rolling hills throughout the airspace which often obstruct the LOS between GCS and UAV. To overcome this limitation, multiple UAVs can be flown to act as relays or as part of a mesh network. One of the problems with this solution is the added expense in flying multiple UAVs. Also, when utilizing a mesh network topology, throughput is limited due to bottlenecks on the last node making connection with the GCS.

## **F. SENSOR DATA MANAGEMENT**

UAS sensors have the capacity to generate huge amounts of data. Large UAS are capable of producing  $\approx 10^{17}$  bits per second (bps) of information.<sup>22</sup> If only a fraction of this data is transmitted it would still easily exceed the data link BW capacity of modern UAS. Most SUAS are equipped with multiple aircraft per system. In most cases, STAR missions are still predominantly performed utilizing only one airborne UAV due to frequency conflicts with other UAVs. However, this paradigm is shifting as experience with flying multiple UAVs increases and the technology to support it advances. The raw data returned from UAV sensors is of little value if the information cannot be synthesized and understood within a time span that permits military decision-makers to act. Three sensor data management gaps have been identified in SUAS are addressed next.

### **1. Instant video playback**

As discussed in Chapter IV, the video received and displayed on the GCS monitor can arrive rapidly making it difficult for an operator to detect features or targets of interest. The lower the altitude of the sensor, the quicker the data will pass on the screen for any given UAV speed. At typical speeds of SUAVs (80 to 100 km/hr), the altitude must be greater than approximately 500 feet to detect a target within a 2.8 second window. Usually when a target is detected the operators will want to see it again right away to verify what they think they saw. Without a video playback capability, the sensor would need to be repositioned in order to again find the target. For moving targets, a video playback capability becomes even more important. Current SUAS operations dictate flying the UAV to a point where the MPO can direct the sensor to get a fix on a potential target within the AOI. Obviously, this becomes significantly more challenging for moving targets and requires a good deal of coordination between the AVO and MPO. A better paradigm would prescribe “flying the sensor” as opposed to flying the UAV and will be discussed in the following chapter.

### **2. Multi-view Retrieval**

When a sensor passes over anything of interest, the operator observes that area from the angle at which the sensor is pointing. In addition to having the record and playback capability mentioned above, the operator should have the ability to retrieve

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<sup>22</sup> Autonomous Vehicles in Support of Naval Operations, The National Academies Press, 2005, p. 208.

images from other sensors taken at different times and from other perspectives. Historical data of the AOI would have to be stored and made easily available to the MCS operator in a timely manner else its value is diminished. To minimize the possibility of information overload on man and machine, the operator could be asked to provide his or her AOR on the user interface. The data management application would ensure that only data within this relevant area is retrieved. Additionally, all stored historical data would necessarily be geo-referenced to ensure consistency with the current view with which it is being compared.

### **3. Image Difference and Change Detection**

The need to rapidly detect and accurately geo-locate a target's location was identified above as a technology gap that impacts several UAS missions. Traditional image registration techniques tend to fail in the presence of complications such as cloud occultation, elevation distortions, and illumination variations and automated registration of oblique low angle views has remained difficult<sup>23</sup>. A technology solution is being developed at Naval Postgraduate School that utilizes software algorithms and an image differencing technique to address this problem. The approach used employs two low cost PC based workstations and a software package called Perspective View Nascent Technologies (PVNT). One computer executes a program that captures images at one second intervals and synchronizes them with received telemetry messages. The other computer running the PVNT software generates telemetry controlled calculated perspective views from received GPS and camera angle coordinates at one second intervals. The combined system manages the sensor data and provides target position estimates with 1-2 meter accuracy.

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<sup>23</sup> A Description of Image Targeting with PVNT Target Location and Sensor Fusion through Calculated and Measured Image Differencing; Wolfgang Baer and Todd Ross Campbell; 2003

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## **VII. TECHNOLOGY SOLUTION DEVELOPMENTS**

### **A. INTRODUCTION**

According to some industry experts, the Joint Strike Fighter will be the last major DoD manned aircraft acquisition. This means that UAS will have to fill the ever widening gap that develops as manned aircraft decline in number. It is critical, therefore, that the U.S. exploit new technology for UAS to the maximum extent possible in order to maintain its current edge and direct the industry in ways advantageous to national security. Additionally, the nature of modern asymmetric warfare is dictating a fundamental paradigm shift from platform to network centric warfare in order to effectively and affordably fight the wars of the 21<sup>st</sup> century. UAS have demonstrated their ability to work in the net-centric environment and warfighters are increasingly requesting their capabilities.

In this chapter, we describe two different ideas or concepts concerning the operation of UAS. The first idea represents the prevailing concept today. It follows naturally from the way we have historically operated manned and unmanned aircraft with the pilot and aircraft at the center of the mission. The current state of technology supports this concept and there is little wonder why it prevails. The second idea proposes an alternative view that places emphasis on the mission as opposed to the pilot and aircraft. Instead of thinking in terms of flying the aircraft, we suggest the concept of “flying the sensor.” The current state of technology has not caught up to this idea, but it is only a matter of time before it does and new UAS system designs should move in this direction.

For SUAS, the technology gaps identified in Chapter VI will be best solved utilizing a software, vice a hardware approach. In this chapter, the reasons that support the pursuit of software over hardware technology solutions are presented. Technology developments applicable to the identified shortfalls are being pursued at NPS. While the potential solutions are focused on advancing the mission support for SUAS, much of this technology has equal applicability to any UAS. It is our hope that this research will

enhance the design of SUAS flight and mission control support systems (FMCSS) and stimulate new ideas and research in the field of UAS.

## **B. DESIGN PHILOSOPHY**

Every good system design process starts with an overarching idea or goal that guides the architect and other system designers. The common goal or “big picture” idea helps designers form a picture in their mind of what the system is suppose to accomplish or behave. The mental picture envisioned has little direct affect on detailed design decisions, but instead provides a framework in which to place the detailed design decisions that will be made at a later stage. Concerning UAS design, one major design philosophy prevails. This approach is described next followed by an alternative approach that will become more appropriate as the services become more net-centric. It is important to note that regardless of the design philosophy chosen, the ultimate goal remains to design a better system that enables warfighters to accomplish their mission in the most effective manner possible with limited resources.

### **1. “Brain in the Cockpit”**

The current paradigm in UAS design centers on the concept of keeping one UAV operator’s head (brain) in the cockpit while leaving his or her body on the ground. System designers want to, ideally, replicate the cognitive powers of a human (perhaps even super-human) in the cockpit with some type of computer processing. Where shortcomings remain, the system is augmented by a remote human operator through a data link to the UAV.

To the extent that we can put an operators head in the cockpit while leaving his or her body on the ground, determines how closely the UAS can perform when compared to its manned counterpart. Similar to a person in a flight simulator or playing a video game (virtual pilot), the pilot on the ground, with the aid of information processors, can control the aircraft as if he or she was sitting in the cockpit. They operate the aircraft under all possible conditions that the aircraft can fly and make decisions when uncertainty and confusion exist. For example, when bearing arms, the virtual pilot will operate under the rules of engagement (ROE) and make tough decisions about when and when not to use



deadly force. With the HIL, the full range of human judgment, intellectual capability and moral character can be brought to bear in any mission.

## **2. “Fly the Sensor”**

An alternate design philosophy takes emphasis off the pilot and aircraft and shifts it to *information*. We have labeled this concept “fly the sensor” to emphasize the importance of a sensor in collecting mission critical information regardless of platform type. This is an important distinction to make now that war is being waged in the Information Age. We don’t care so much about where or what platform the information comes from, as we do about its qualities such as accuracy and timeliness. To enable this warfighting philosophy, the DoD has invested resources to build a Global Information Grid (GIG) that will allow the military to conduct Network Centric Warfare (NCW). NCW can be defined as:

an information superiority-enabled concept of operations that generates increased combat power by networking sensors, decision makers, and shooters to achieve shared awareness, increased speed of command, higher tempo of operations, greater lethality, increased survivability, and a degree of self-synchronization<sup>24</sup>.

The “fly the sensor” design philosophy is consistent with the concept envisioned in NCW and places more human attention on mission critical information as opposed to tasks involving UAV flight.

## **C. HARDWARE VERSUS SOFTWARE SOLUTIONS**

People living today are witnessing a technological explosion similar to, but more rapid, than the technological growth experienced during the industrial revolution of the 19<sup>th</sup> and early 20<sup>th</sup> centuries. During that period the economy was dominated by machinery and manufacturing. Today the developed nations of the world have entered a new economic era, sometimes referred to as the digital revolution, being led by advancements in computer hardware and software. The time between significant technological developments is rapidly decreasing and we have reached the knee of the curve in an evolution of technology. Author and inventor Ray Kurzweil has described

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<sup>24</sup> Network Centric Warfare: Developing & Leveraging Information Superiority, David Alberts, John Garstka, Frederick Stein. CCRP Publications series, February 2000. p. 2.

this phenomenon as the “Law of Accelerating Returns”<sup>25</sup> and predicts no limit to the exponential growth of technology.

In today’s information age, technology advances can be broadly classified into two major categories: hardware and software. While hardware is a general term which includes any type of machine, tool or other physical components, the hardware making the most impact in the information age, is computer hardware. Computer hardware was developed before any software was produced. Indeed computer hardware *had* to come first, for without computer hardware it is impossible to run any software. The computing field is only about 60 years old beginning on the tail end of the industrial revolution, but its growth is without precedent in the world of engineering. The most significant hardware development to occur in the history of computing is the integrated circuit. Starting with the invention of the transistor in 1947, which replaced vacuum tubes, integrated circuits with millions of transistors on one substrate were developed and have now become ubiquitous.

Gordon Moore, co-founder of Intel, famously noted in a 1965 article of *Electronics Magazine* that the complexity (interpreted as the number of transistors) of



Figure 16. Gordon Moore

integrated circuits doubles roughly every year. In a follow-on article in 1975 he adjusted this estimate to every two years to account for chip complexity.<sup>26</sup> This trend has held

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<sup>25</sup> The Age of Spiritual Machines; Ray Kurzweil; 1999.

<sup>26</sup> Technology@Intel Magazine entitled: From Moore's Law to Intel Innovation—Prediction to Reality; Radhakrishna Hiremane; April 2005.

remarkably true (Figure 17) and is believed by many, that it will last for at least another 10 to 20 years before a fundamental physical limit is reached.

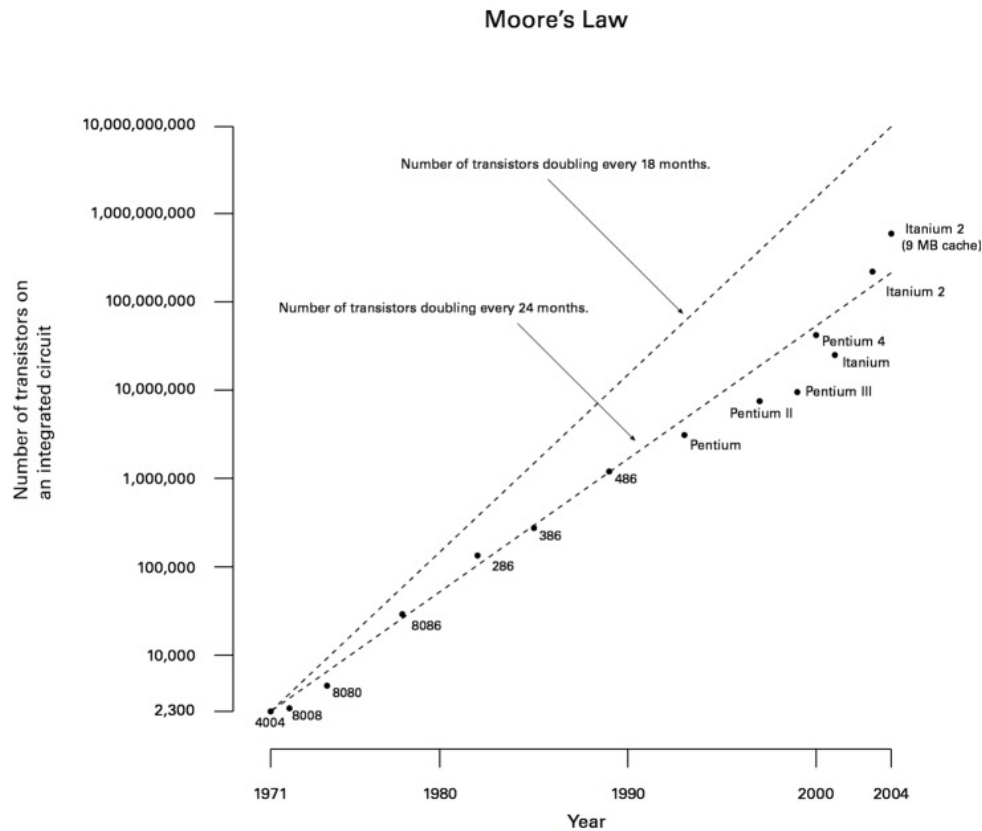


Figure 17. Moore's Law (From: website: [http://en.wikipedia.org/wiki/Image:Moore\\_Law\\_diagram\\_%282004%29.jpg](http://en.wikipedia.org/wiki/Image:Moore_Law_diagram_%282004%29.jpg) accessed July 28, 2006)

Software is a distinct technology that consists of digital data or programs residing inside a computer's hardware (memory). Software can't be seen or felt and takes up no physical space within the hardware. Computer hardware and software technologies must work together to both produce value. As the computer hardware industry races ahead providing more powerful capabilities, and better-faster-cheaper computing and communication devices, a software gap has developed that prevents us from exploiting all the capability and value that these hardware devices promise. So which technology provides more "bang for the buck" and which technology needs more focused attention and resources when designing future SUAS flight and mission control support systems (FMCSS)?

It is hard to definitively or quantitatively answer this question, however, the research conducted while writing this thesis points in the direction of software, particularly image processing and data handling applications that can improve the effectiveness of STAR missions. The computer hardware improvements realized, for example, as a result of Moore's Law, will continue unabated regardless of the direction taken by the designers of SUAS. Software developments, on the other hand, that specifically add value to SUAS will require focused efforts on the part of SUAS designers. New software developments offer the possibility to significantly improve the functionality of SUAS by shifting more work off humans and accomplishing it in the software.

The same argument advocating software over hardware improvements can be applied to airframe hardware as well. Airframe hardware improvements, such as inertially stabilized gimballed cameras, will usually result in added weight to the UAV platform. Adding weight lowers endurance for the same fuel load and increases total costs. Figure 18 shows the empty weight and cost data for several DoD UAVs. Today the average cost for the UAVs listed is \$1500 per pound of empty weight. When the payload is included the cost jumps to approximately \$8000 per pound of payload weight

System	Aircraft Cost, FY04\$*	Aircraft Weight, lb*	Payload Capacity, lb	System Cost, FY04\$	Number Acft/System
Dragon Eye	\$28.5K	3.5	1	\$130.3K	3
RQ-7A Shadow	\$0.39M	216	60	\$12.7M	4
RQ-2B Pioneer	\$0.65M	307	75	\$17.2M	5
RQ-8B Fire Scout	\$4.1M	1,765	600	\$21.9M	4
RQ-5A Hunter	\$1.2M	1,170	200	\$26.5M	8
MQ-1B Predator	\$2.7M	1,680	450**	\$24.7M	4
MQ-9A Predator	\$5.2M	3,050	750**	\$45.1M	4
RQ-4 (Block 10) Global Hawk	\$19.0M	9,200	1,950	\$57.7M	1
RQ-4 (Block 20) Global Hawk	\$26.5M	15,400	3,000	\$62.2M	1
*Aircraft costs are minus sensor costs, and aircraft weights are minus fuel and payload capacities					
** Internal payload weight capacity only					

Figure 18. UAS And UAV Costs And Weights (From: UAS Roadmap, 2005)

(Figure 19). Note, however, for the only SUAV listed, the Dragon Eye, the cost per pound is significantly greater in both categories—approximately \$30,000 per pound.

Any airframe hardware technology improvements would have to be made with very light weight materials to keep costs from skyrocketing. To improve SUAS capability with hardware, the most cost effective solutions will likely be achieved if they are applied to the ground or mission control stations.

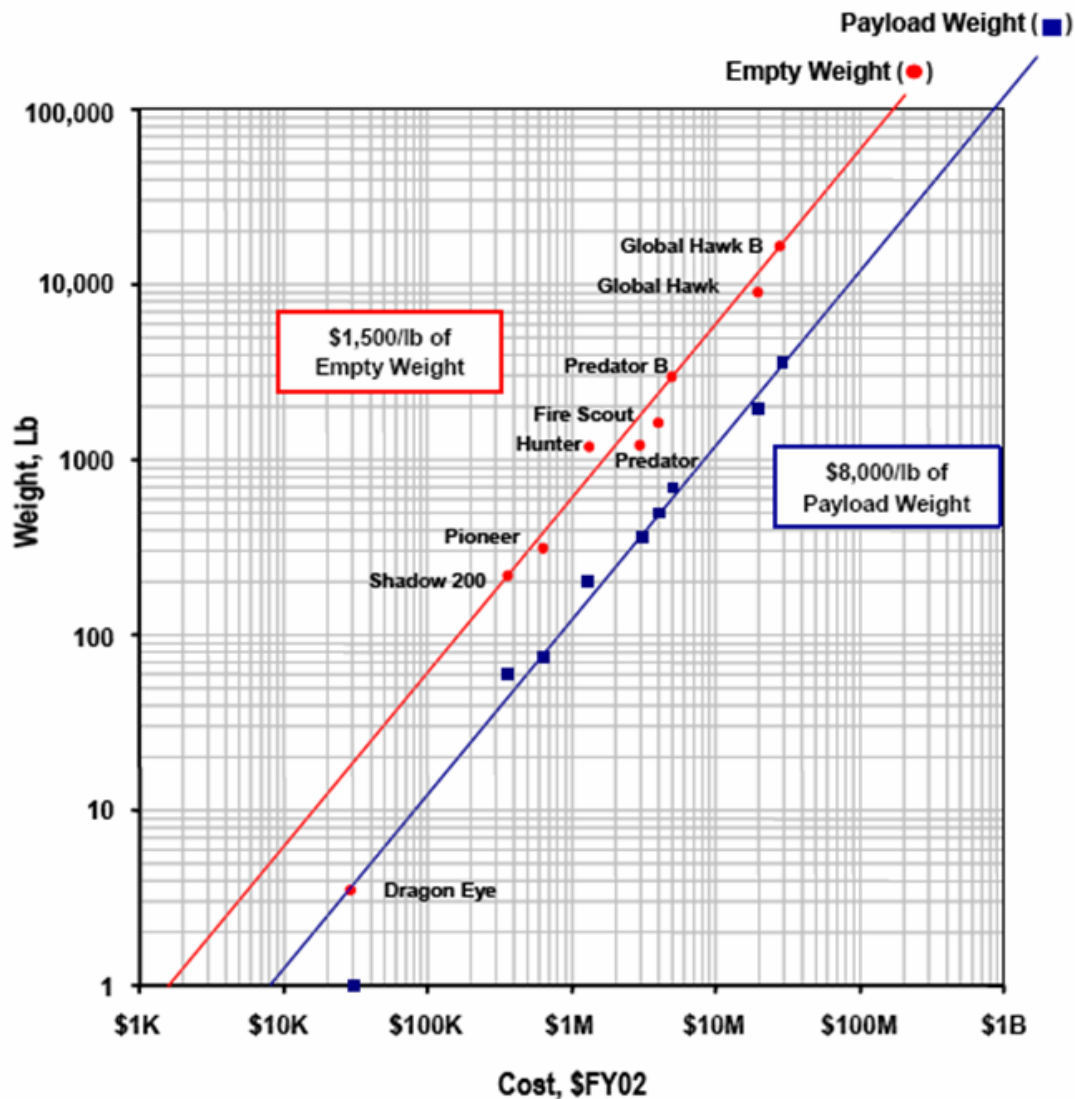


Figure 19. UAV Capability Metric: Weight V. Cost (From: UAS Roadmap, 2005)

In this chapter software solutions are presented as a way to fill the technology gaps identified earlier. The hope is that these potential solutions may lead to significant improvements in the design of SUAS FMCSS.

#### **D. GEO-LOCATION**

A vision-based target tracking system has been developed and is being refined at NPS. The system has the potential to significantly improve the process of identifying target coordinates obtained in STAR missions performed by SUAS (or any UAS). The system was utilized in a field experiment discussed in the next chapter and is described in the paragraphs that follow.

Video captured by an EO camera aboard a SUAV is transmitted on a 2.4 GHz link to the GCS. The GCS uses off-the-shelf PerceptiVU image processing software<sup>27</sup> which allows an operator to select and lock on a target displayed on the GCS monitor. The PerceptiVU software provides coordinates of the centroid of the target selected by the operator. These coordinates are then employed by control and filtering algorithms implemented on the NPS ground station.<sup>28</sup> Flight tests conducted by NPS have demonstrated the ability to provide 20-30m accuracy in target geo-location obtained within 15-20 seconds of tracking.

The system can operate within a mesh network that allows data sharing between all nodes connected to the system. In addition to the real-time tracking and estimation algorithms employed by the GCS, the UAVs telemetry and onboard images are sent to a Perspective View Nascent Technologies (PVNT) workstation that enables more precise geo-location measurements to be obtained. The PVNT is a general software package addressing the generation and utilization of metrically accurate one-meter terrain databases for measurement, analysis, and visualization of live/virtual tactical battlefield situations. The system implements a unique image registration technique that allows near real time (NRT) view projections with elevations included. Other techniques tend to concentrate on the alignment of actual images taken from various angles and tend to fail in the presence of complications such as cloud occultation, elevation distortions, and illumination variations. PVNT performs registration between a measured image and an image calculated from a terrain database as opposed to registering two or more images directly. Using this approach, the viewpoint can be modified and a new image generated

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<sup>27</sup> PerceptiVU Inc, [www.Perceptive.com](http://www.Perceptive.com)

<sup>28</sup> Ick H. Whang, Vladimir N. Dobrokhodov, Isaac I. Kaminer, and Kevin D. Jones, "On Vision-Based Target Tracking and Range Estimation for Small UAVs," *AIAA 2005-6401, AIAA Guidance, Navigation, and Control Conference and Exhibit*, 15 - 18 August 2005, San Francisco, CA.

that includes elevation distortions, surface occultation, and to some extent atmospheric effects. This procedure enables comparison of images which have to a large extent been corrected for these parameters.

The PVNT system consists of two standard PC computers. One executes an interface program that captures and displays six seconds of images each at one second intervals and synchronizes the images with telemetry messages. The second computer running the PVNT software generates telemetry controlled calculated perspective views from received GPS and camera angle coordinates at one second intervals. The calculated and measured views are then registered and differenced to highlight the target.<sup>29</sup> When the calculated and measured view are close enough to perform target location, the PVNT operator then performs a final target location by clicking on the location in the calculated image where the target would appear if it were in the database. The advantage of this vision-based target tracking approach is that the accuracies of target location is determined almost exclusively by the accuracy of the database and does not require precision gimbals or accurate UAV location data. The combined system provides target position estimates with 1-2m accuracy and has been successfully demonstrated in several field experiments conducted by NPS at Camp Roberts.<sup>30</sup> Figure 20 shows the FOV from two sensors and the calculated perspective views generated by PVNT.

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<sup>29</sup> W. Baer, T. Campbell, "Target Location and Sensor Fusion through Calculated and Measured Image Differencing," *Signal Processing, Sensor Fusion, and Target Recognition XII*, Ivan Kadar, Editor, Proceedings of SPIE Vol 5096(2003) p 169.

<sup>30</sup> Vision Based Target Tracking and Network Control for Mini UAVs; I. Kaminer, V. Dobrokhodov, K. Jones and W. Baer.

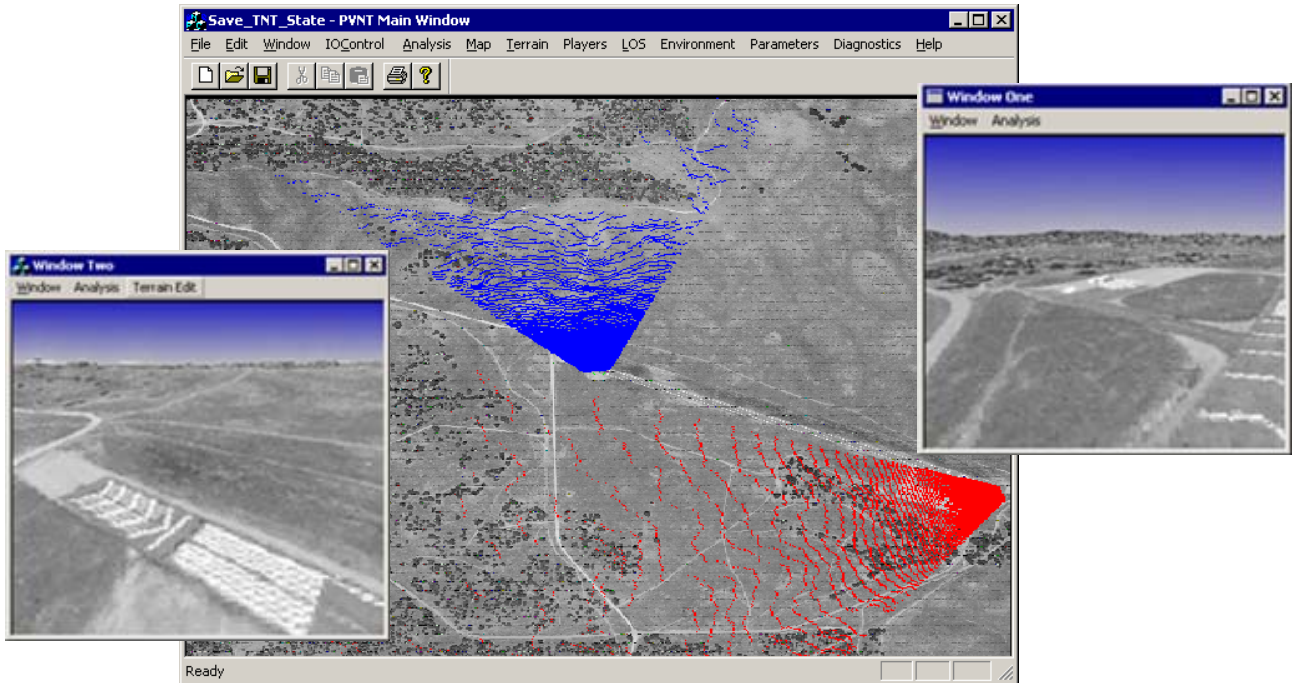


Figure 20. PVNT FOV and Calculated Images

## E. IMAGE STABILITY

Image stability can be improved utilizing hardware or software techniques. Hardware solutions are categorized as active or passive. Passive stabilization techniques are purely mechanical and rely on the "balanced beam" phenomena. The 'beam' will resist base motion from affecting the camera positioned at the end of it because of the inherent inertia of the balanced beam. Active hardware systems are ones that utilize DC power, sensors, electronics and motors attached to gimbal rings to correct base motion from affecting the camera.<sup>31</sup> For UAS, hardware solutions are acceptable only on larger platforms where weight and power limitations do not restrict their use.

For SUAS with payloads one or two orders of magnitude smaller than larger UAS, ultra light weight inertially stabilized gimbaled camera systems or more robust image processing techniques, or a combination of both, offer the only practical solution. There are several companies that currently market software products that claim to improve video stability.

<sup>31</sup> Nettman Systems International website: <http://www.camerasystems.com/gyrostabilization.htm>, accessed 4 September 2006.



### **1. Tactical Image Processing Software (TIPS)**

TIPS made by Brandes Associates Incorporated is a portable system designed for small and mini-UAV missions. It employs enhancement algorithms that penetrate fog, haze and mirage artifacts commonly found in the raw input video stream. The video image stream data can be stabilized in 4-dimensions (X and Y, rotation, scaling and zooming) to counter vibration encountered on SUAV payloads. It accepts most video input formats providing day and night video image enhancement. TIPS performs as a passthru system with a delay of no more than 2 frames.

The TIPS system was operationally tested with PVNT. The application automatically cropped and readjusted the image position to the center of the monitor with every frame capture. One observer reported a fuzzy picture containing artifacts in the displayed image and questions whether the advertised preprocessing capability to provide contrast enhancement and image sharpening was actually achieved. Company website is accessible at: [http://www.brandes-assoc.com/technology\\_insertion%20v2.HTML](http://www.brandes-assoc.com/technology_insertion%20v2.HTML)

### **2. SteadyEye™**

Made by DynaPel Systems Incorporated, SteadyEye is an application that integrates with analog Color, B/W, IR or thermal cameras. The system advertises the ability to correct shake in the horizontal and vertical direction as well as shake from rotation and zoom. The system was tested with the NPS SUAV with only marginal results. One operator suggested that it would produce acceptable results if used in conjunction with inertial stabilization. Company website is accessible at: <http://www.dynapel.com/index.shtml>

### **3. VICE**

Designed by Sarnoff® Corporation, VICE (Video Imagery Capability Enhancement) claims a host of real time video processing capabilities on a standard PC. The software provides electronic stabilization to remove camera shake and real time mosaicing to create panoramic views of a scene as the camera pans. It has an automatic moving target indicator (MTI) that can graphically show or alert operators to a moving target in the image view. The software can display 3D video for up to eight video feeds on reference imagery or maps and merge other forms of data with the video.

The VICE system was recently tested for compatibility with the NPS PVNT software in field experiments conducted at Camp Roberts. The experiment successfully demonstrated the ability to capture and transfer stabilized imagery to PVNT. The successful integration will lead to future experiments to see if images stabilized through the mosaic process would improve SUAS STAR mission performance. Company website accessible at: <http://www.sarnoff.com/>

#### **4. Future Possible Solutions**

In general, the problem with image stabilization occurs when multiple images are superimposed on one another. Most software applications employ algorithms that take averages of pixel contrast to reconstruct images. While this may produce a more stable image, its value is degraded because the image tends to become “fuzzy.” Potential solutions to this problem may lie in innovative new algorithms that do more than simply take pixel averages. Two areas are suggested for research that could possibly minimize or solve this problem: 1. Radar mono-pulse scanning and 2. saccadic eye movement.

Radar mono-pulse scanning is used in fire-control tracking radars and employs one radar pulse to obtain a target’s range, bearing and elevation angle. Mono-pulse tracking radars achieve higher target resolution by comparing the target location in multiple pulses, hence it is not the pulse width, but the envelope between multiple pulses that determines angular resolution. This radar technique can be accomplished electronically requiring no mechanical action and is not subject to errors due to rapid fluctuation of the returned echo signal amplitude as the target moves (scintillation errors).

Saccadic eye movements are very rapid simultaneous movements in both eyes in the same direction. These movements occur naturally in human vision so that the point of interest will be centered on the fovea, the high resolution central part of the retina. Human vision has evolved to make these adjustments as fast as possible and saccades are the fastest movement of the external part of the human body. Even when fixated on a stationary target, micro-saccades are required to refresh the image cast on the retina because receptors in the retina are only responsive to *changes* in luminance. These eye movements occur naturally and are not perceived as image instability in the brain.

Both mono-pulsing radar and saccadic eye movements are examples by which image clarity and resolution are improved with multiple measurements. Not all image stabilization techniques employ visual methods, and therefore stabilized images are often less clear, although stable. Further study is needed to determine how these techniques could be applied to improve image resolution. It is hoped that algorithms may be created based on the physics of mono-pulse scanning or saccadic eye movements that reduce or eliminate the distortions observed in image stabilized video.

#### **F. WHAT-WHERE DISPLAY**

Chapter VI identified a gap in the ability to simultaneously display what a sensor is pointing at while providing context about where the sensor is located. The PVNT system offers a possible software solution to this problem. By mapping the actual measured image collected from an EO sensor to the video cones displayed in Figure 18, an operator would be able to see both what the sensor is looking at, as well as context on where the sensor is located. This idea was tested in the field experiment described in the next chapter. It should also be pointed out that the PVNT system can project the returned images on other map displays besides the “god’s eye” view shown in Figure 20. For example, the images could be mapped onto a cartographic map as shown in Figure 21.

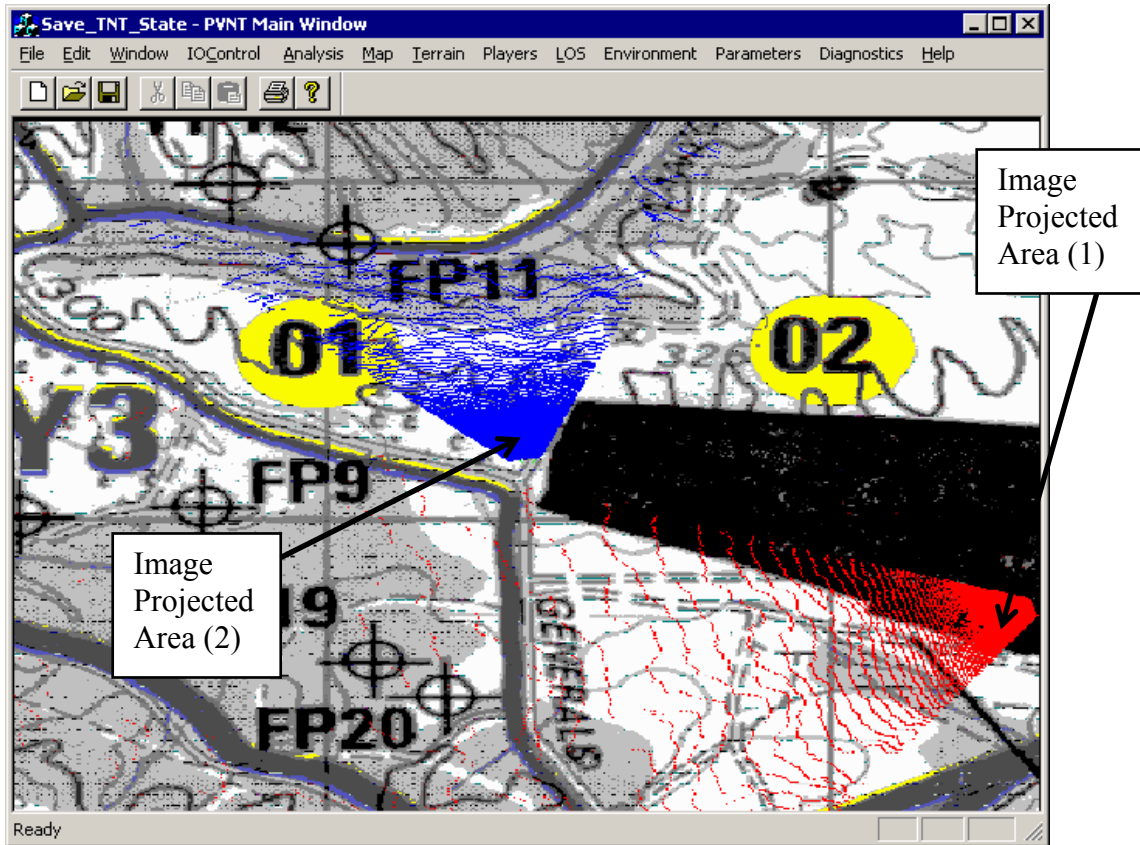


Figure 21. PVNT Perspective Views on Cartographic Map

The ability to project multiple images on one display is a step in the direction toward lowering the human to UAV ratio discussed earlier. This simultaneous what-where display could be combined with “fly-the-sensor” technology allowing UAV flight to be controlled directly through the manipulation of sensor projections potentially lowering the cognitive load placed on UAS operators.

## G. SENSOR DATA MANAGEMENT

This section addresses two of the three technology gaps related to sensor data management identified in Chapter VI. These technology solutions were tested in a recent field experiment and will be discussed in Chapter VIII.

### 1. Instant Video Playback

The PVNT system provides a means to capture, display, record and playback video frames transmitted from EO sensors. The system has been designed to allow an operator to playback video frames recently displayed. Ideally the system could retrieve

video captured at any time during the mission, however, practical limitations such as disk space limit the amount of playback allowed. This playback capability may enhance mission success by precluding the necessity for a UAV to fly over an area previously viewed. The results of this video playback capability are discussed in Chapter VIII.

## **2. Image Difference and Change Detection**

In addition to providing highly accurate geo-located target coordinates as described above, PVNT can use its excellent and accurate data presentation to identify changes in terrain. Terrain changes can be produced naturally due to weather, earthquakes, or volcanic activity; or by people constructing buildings or simply placing objects in different positions. Detecting terrain changes with SUAS can be quicker and safer than sending people or manned aircraft or over hostile areas. Using SUAS is also a better alternative than satellite reconnaissance because satellites are predictable allowing an adversary to deceive or hide important information.

## **H. PRODUCT-LINE ARCHITECTURE**

Table 6 in Chapter IV identified important functions required for various UAS missions and listed where these functions are performed within the five subsystems of a generic UAS. These subsystems were laid out in the functional layer model of Figure 12 to illustrate where these subsystems are located within a typical UAS. The functional divisions are separated in time by approximately two orders of magnitude each. The values indicated on the figure are representative of the current technology level that SUAS operate. Ideally, we would like everything to happen as efficiently as possible, exactly when needed and consuming as few resources as possible. However, the other design characteristics listed on the figure must also be considered and tradeoffs will have to be made when designing SUAS (or any system).

To achieve the desired mission success, the functions listed in Table 6 must be performed by entities or components i.e., humans, hardware, or software or some combination. These components must be connected together in an architecture or framework that permits information exchange between them. Besides the communication subsystem represented by the clouds in Figure 12, data is passed between components through application interfaces consisting of:

- Transport protocols i.e., TCP/IP, UDP, etc.
- Web addresses i.e., URLs
- Message data definitions i.e., Cursor on Target (CoT)

Most SUAS contain a variety of similar application requirements that can be designed with mostly generic software. To maximize the interoperability of the software components that may come from a variety of different vendors, formal interface definitions are required. To achieve the desired result, a product-line architecture is recommended as the best approach [2, 3]. A product-line architecture defines a set of reusable generic components and specifies how data and control should flow among them to solve application problems<sup>32</sup>. A well designed architecture conducive to “plug and play” operation will encourage developers to create interoperable components of increasing quality and capability.

The functional model discussed above is a first cut attempt to define the functional components and framework in which a generic SUAS FMCSS may be designed. The next step requires the development of formal data specifications for use in a product-line architecture. A rapid benefit of this approach would be the reduction of ad-hoc face-to-face meetings of individuals that are necessary to work out data management problems currently experienced in the NPS field experiments.

## **G. BANDWIDTH**

While some of the missions identified in this thesis may not require huge amounts of bandwidth, the primary reconnaissance missions as well as combat search and rescue (CSAR) and some communication relay missions depending on the data relayed, all require significant amounts of bandwidth to transmit imagery data. Technologies that enable more processing to be accomplished onboard the UAV only slightly help to mitigate this problem. As the vehicle becomes more autonomous, less data is needed between GCS and UAV. Unfortunately, the command and control data is only a small fraction of the total amount of information that must be transmitted. As the military

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<sup>32</sup> Model-based Communication Networks and VIRT: Filtering Information by Value to Improve Collaborative Decision-Making; Dr. Rick Hayes-Roth, Naval Postgraduate School, April 2005.

strives to achieve the objective of net-centricity, issues with bandwidth limitations are likely to continue in the foreseeable future and will continue to receive focused attention.

One possible solution involves using a mesh network as opposed to individual direct links. In a mesh network, multiple nodes e.g., UAVs, can be used to transmit data much like routers in a ground based network. By increasing the number of nodes the number of possible paths available to transmit data increases. Theoretically, with more pathways available, there exists a larger “pipe” i.e., greater bandwidth, in which to transmit data.

The mesh technique has recently been tested in the NPS field experiments with unmanned ground and aerial vehicles. The technology tested is made by ITT and uses a proprietary protocol similar to the IEEE 802.16 protocol. So far the technology has produced less than desirable results. When multiple users tried to access data from different individual UAVs, a new data stream from the UAV platform was generated over the mesh network to the receiving clients. As a result, when more than one user wanted to receive video, the network load capacity was exceeded and performance became difficult.

To solve this problem, digital video from the UAV’s was transmitted to a single Pelco receiver where it was reconverted to analog video, sent via a cable to the TOC and reconverted to digital video where it could be locally distributed on higher bandwidth lines in the TOC.

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## VIII. FMCSS FIELD EXPERIMENT

### A. INTRODUCTION

Every academic quarter a series of experiments coordinated by NPS and Special Operations Command (SOCOM) is conducted in cooperation with a number of other government organizations, industry and universities. The bulk of the experiments take place at Camp Roberts located approximately 120 miles south of NPS. Much of the research is focused on unmanned air and ground vehicle operations as well as the network supporting these operations. Two experiments are described in this chapter; one took place in early June of 2006, the other during the third week of August 2006. Officially the experiments were designated TNT-06-3 and TNT-06-4 respectively.



Figure 22. TNT UAVs

### B. TNT EXPERIMENT 06-3

The Flight and Mission Control Support System's (FMCSS) overarching objective was to support flight coordination, feature identification, and target location for multiple SUAVs. Specifically, experiment 06-3 objectives were to:

- **Synchronized Image Playback:** Test image capture, storage, and playback function to support image navigation and feature identification and target location.

- **Multiple UAV Sensor Projection Display:** Test multiple SUAS sensor on map projection display to enhance the operator's ability to manage multiple data streams at once.
- **Interface Testing:** Define and test general SUAS interfaces for video and telemetry to provide mission support for alternative UAV platforms.

The discussion that follows will cover the salient portions of first two objectives.<sup>33</sup>

## 1. General Setup

Figure 23 illustrates the layout of SUAS FMCSS that was setup in the Camp Roberts Tactical Operations Center (TOC). PC interface machines, IF-1 and IF-2 in the figure, can receive video and GPS telemetry from two UAVs. IF-1 and IF-2 capture and format data for transmission to the middle PVNT PC. The PVNT machine performs image geo-referencing, target coordinate determination and provides image display locally or to larger situational awareness (SA) screens within the TOC.

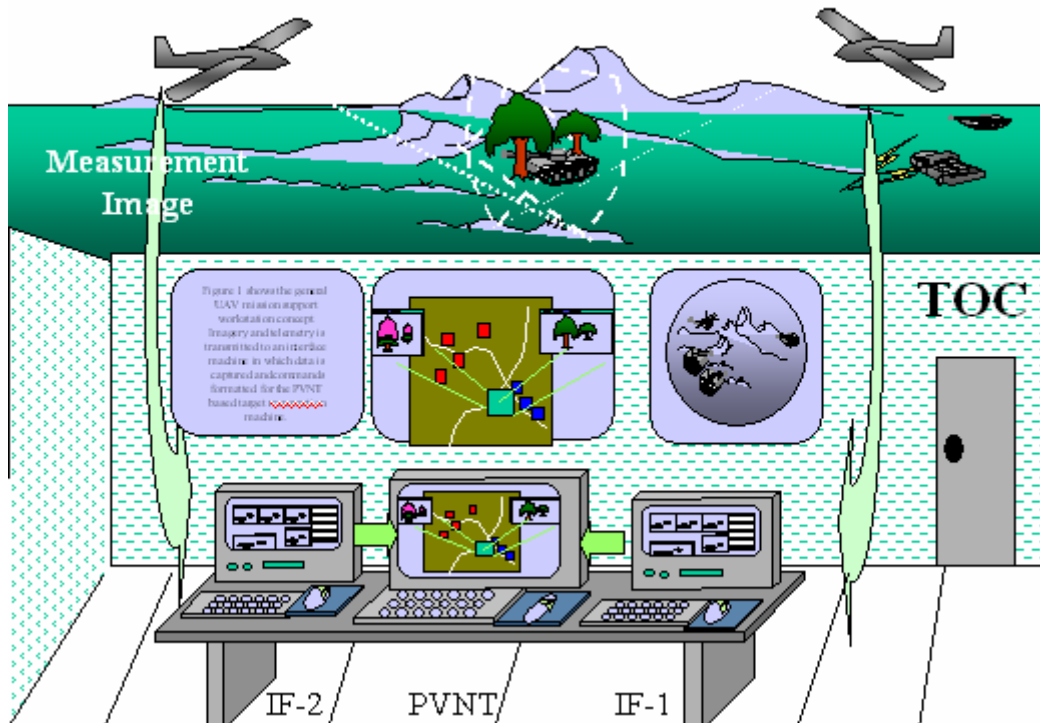


Figure 23. SUAS FMCSS

<sup>33</sup> Full technical details and thorough description of the experiment can be found in the final report entitled: UAV Flight and Precision Targeting Mission Control Experiment 20 Report for TNT-06-3; Dr. Baer, June 16, 2006.

## **2. Detailed Schematic**

Figure 24 shows the connectivity, equipment and software configuration for experiment TNT-06-3. Telemetry paths are shown as solid arrows while video data is depicted with wide arrows. Two video streams are monitored and selected frames are transferred to the PVNT machine for local display and also for projection onto larger wall screens within the TOC for wider review.

Special interfaces were established to both NPS UAVs using Pelco transmitters. One transmitter on each UAV broadcasted video over a mesh network to the GCS where it was then placed on the TOC network where it became accessible through browser based Pelco plug-ins. UAV telemetry was transmitted to a second Pelco receiver which provided telemetry directly to the MCS interface machines through Rs-232 connections.

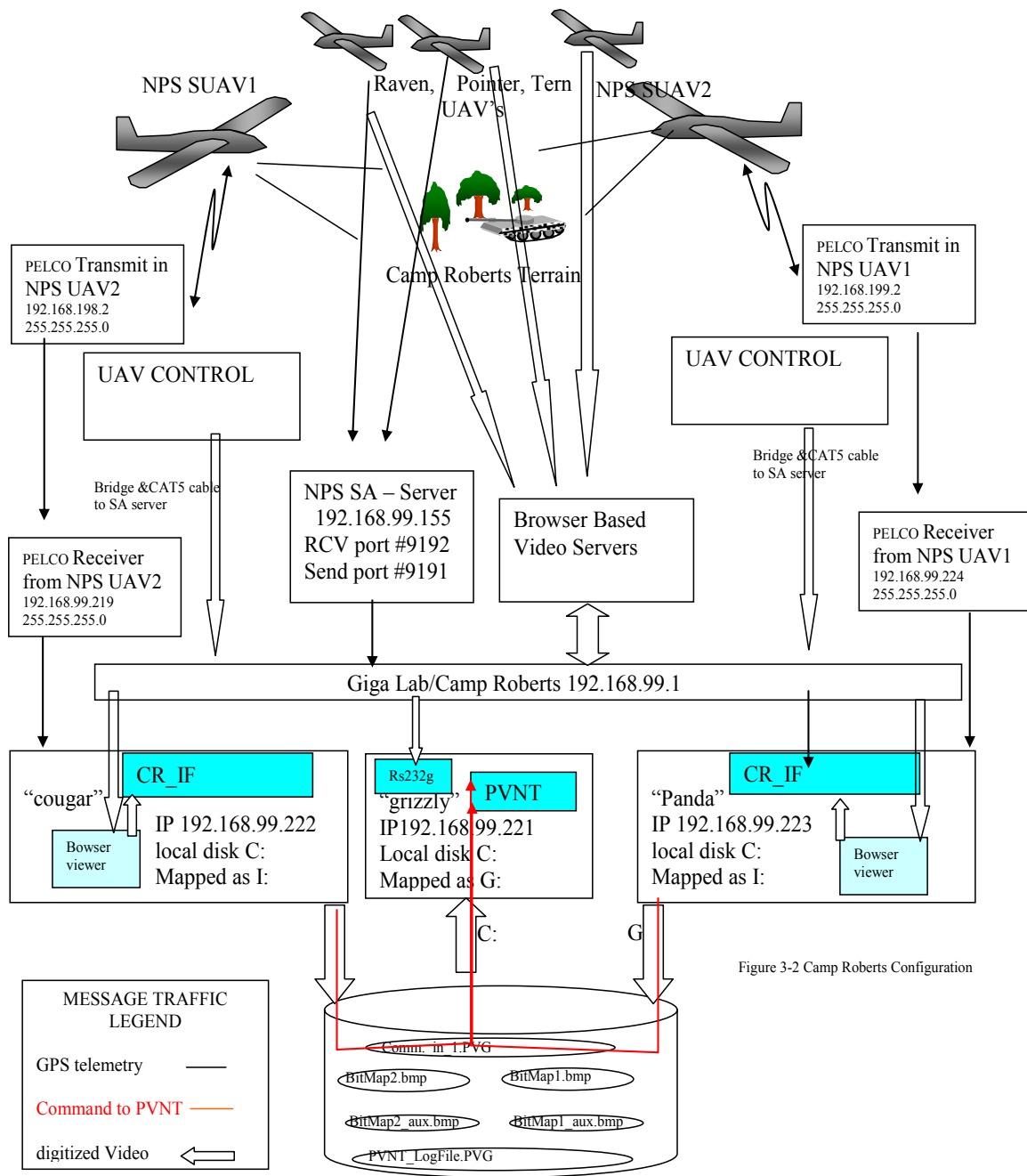


Figure 3-2 Camp Roberts Configuration

Figure 24. Detailed Schematic

### 3. Synchronized Image Playback

This part of the experiment was designed to address the technology gap identified in Chapter VI concerning sensor data management. The previous chapter suggested a potential solution to this problem could be developed that would allow an operator to essentially “rewind” previous video data returned in order to perform a more detailed

analysis. To test the ability to display, record and playback a series of frames, code was written by NPS professor Dr. Wolfgang Baer and installed onto the interface machines depicted above. Our hope is that a low cost software solution can be developed that will improve an operators effectiveness while performing surveillance type missions, such as STAR. A brief description of this software is provided below<sup>34</sup>.

The software component, called Video Time Trail Playback, provides a means to display, record and playback a series of frames, called the Window. A trail consisting of several (9 max) sequential frames is displayed on separate windows in the interface machine. Figure 25 below shows a typical screen snapshot showing the display.

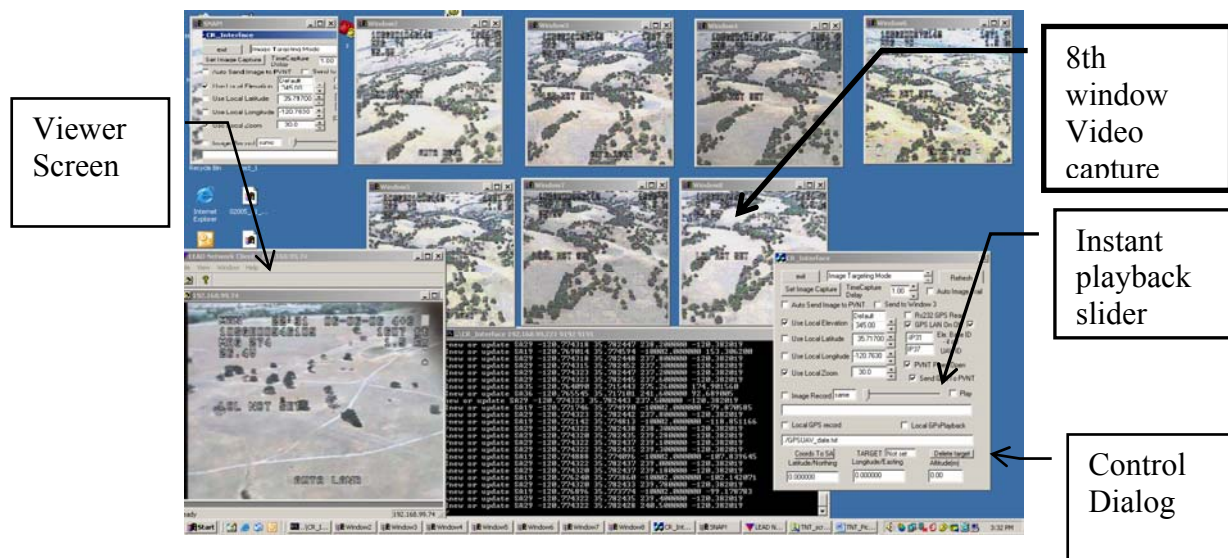


Figure 25. CRP\_Interface Program Screen

Incoming video frames from a SUAV sensor are displayed in the large viewer screen shown on the left side of Figure 21. An operator uses this view to look for and detect features of interest. The nine trailing frames provide a display of the last 9 captured frames. The capture rate is selectable but 1 second is typical.

In earlier experiments it was found that 9 seconds was inadequate for an operator to perform useful analysis on the incoming frames. The Video Time Trail Playback

<sup>34</sup> A detailed description is provided by Dr. Baer entitled: VideoTimeTrailAndPlaybackFunction.doc; April 20, 2006.

software component was designed to allow an operator to select a buffer size (limited only by disk storage capacity) that would store video frames that could be played back for comparison and analysis. A disk buffer and slider control was added, set to a default value of 100 frames, to allow instant image playback. Frame telemetry is synchronized and recorded with each frame so that its geographic location can be determined. The trail and image manipulation features are expected to provide the operator context to individual frames and facilitate both target identification and location. The intent was to evaluate technology trade-offs in global system functions, which enhance mission success, and see how much the Video Time Trail Playback component helps.

The experiment succeeded at recording and providing instant image playback during several flights. However, orientation data was never received and the limited position data was delayed between 5 and 10 seconds making geo-referenced playback impossible. A direct data interface to the NPS SUAV designed to provide on-time position and attitude telemetry was never achieved due to wind and communication difficulties. These difficulties were overcome during a repeat experiment in the TNT-06 trials described below.

#### **4. Multiple UAV Sensor Projection Display**

This part of the experiment was also designed to address a sensor data management gap as well as the simultaneous display of what and where video information. In this case the problem concerns providing a video display that contains both what and where information simultaneously while conducting STAR missions. Typically two operators at the GCS are involved to conduct operations involving one UAV; an air vehicle operator (AVO), and a mission payload operator (MPO). The AVO will observe a situational analysis (SA) display that provides context concerning the location of the UAV. The MPO will focus his or her attention on a separate display containing the real time returned video. Mission effectiveness is affected by how well both operators coordinate with each other to “drive” the UAV and analyze the returned reconnaissance data.

In this experiment, the solution developed employs a software algorithm written by Dr. Baer that projects video imagery from multiple UAVs (two in this case) onto a single large map or perspective SA display. The goal is to provide a low cost software

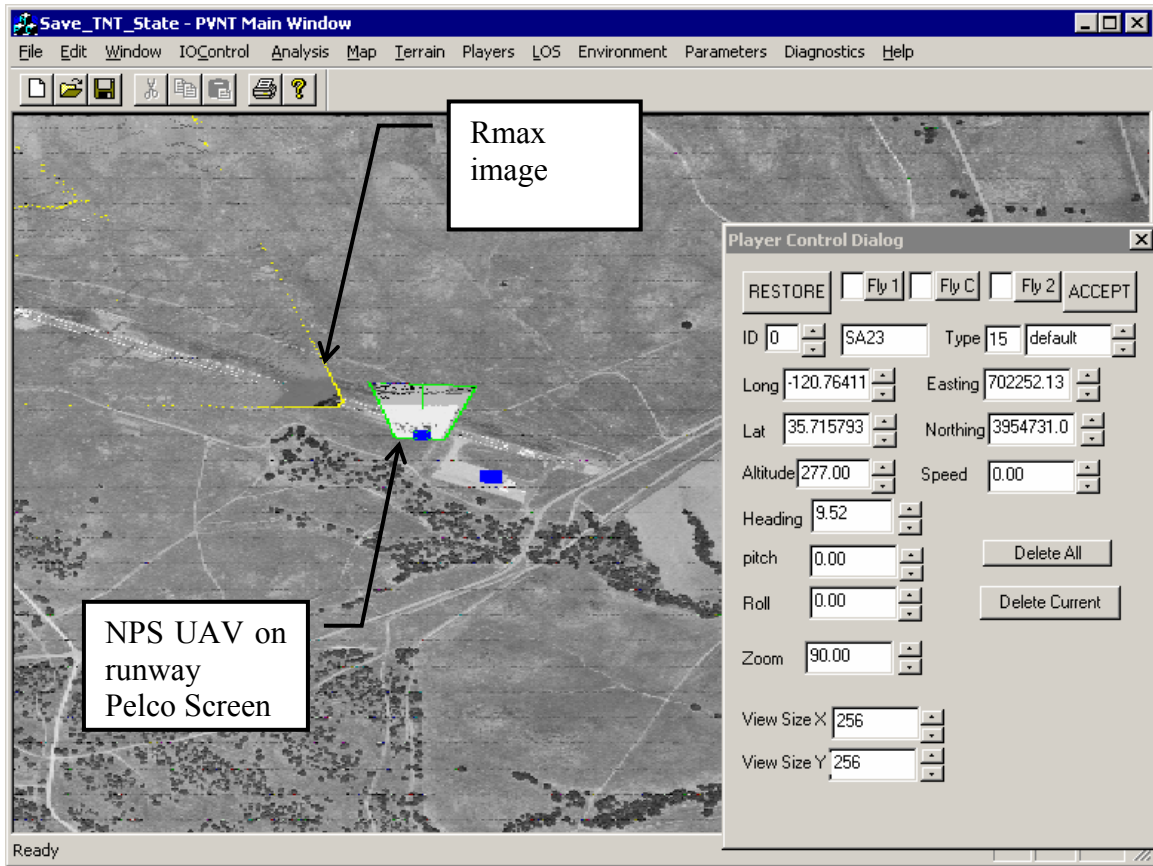
solution that can be implemented in a MCS that will improve operator effectiveness while performing STAR missions. A successful solution will help a single operator understand, manage and control sensor data from multiple UAV's simultaneously. At the time of the experiment, bandwidth limitations prevented real time video from being displayed so only captured imagery was transferred. The intent of this experiment was to determine if the proposed solution could be implemented. If so, new display technology development that fuses multiple real time data streams on one overview would be justified. In the future, this display could be used to expand the “fly the sensor” concept to “fly the swarm of sensors.”

Imagery from two UAVs, the Rmax and NPS SUAV, was captured and transferred to the PVNT display. Figure 26 on the next page shows the two captured images projected onto a map display. Due to technical difficulties with the NPS SUAV, no live image was projected. Instead the white content shown is due to data from the PELCO transmitter that occurs when no video data is available.

The experiment successfully demonstrated that two images could be sent to the PVNT workstation and projected onto the map display at 1.5 fps for each image. However, the geo-location accuracy was poor due to lack of and, in most cases, unavailability of timely position and camera orientation data for the UAVs.

Another observation was made concerning the image viewed on the screen. We noticed that screen resolution collapses near the apex of the viewing cone. As the image is squeezed into a smaller area on the screen, less pixels are available to display it and clarity is lost. While the cone map projection is a good idea, it can not replace the additional view window at this time.





Rmax Captured image



Calculated image 10M high



Figure 26. Rmax and NPS UAV Image Projections on Map Display



### C. TNT EXPERIMENT 06-4

Similar to experiment TNT 06-3, the FMCSS overarching objective for TNT 06-4 was to support flight coordination, feature identification, and target location for multiple SUAVs. TNT 06-4 had three objectives:

- **“Fly-the-Sensor:”** Test the ability of the FMCSS to control the sensor of the NPS SUAV in order to facilitate feature and target tracking
- **Image Stabilization:** Integrate the Sarnoff VICE system with the FMCSS in order to evaluate the ability of the mosaic capability to supply electronically stabilized imagery to down stream search, feature identification, and target tracking systems.
- **Message Standardization:** Test message format and integrate telemetry in order to receive data and provide mission support services for all UAVs.

The discussion that follows will cover the salient portions of first two objectives<sup>35</sup>.

#### 1. General Setup and Schematic

The general setup for TNT 06-4 is similar to TNT 06-3 with the exception that only one interface machine is required. Figure 27 illustrates the FMCSS schematic with one CR-IF machine.

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<sup>35</sup> Full technical details and thorough description of the experiment can be found in the final report entitled: TNT-06-4 Individual Experiment AAR Executive Summary; Dr. Baer, September, 2006.

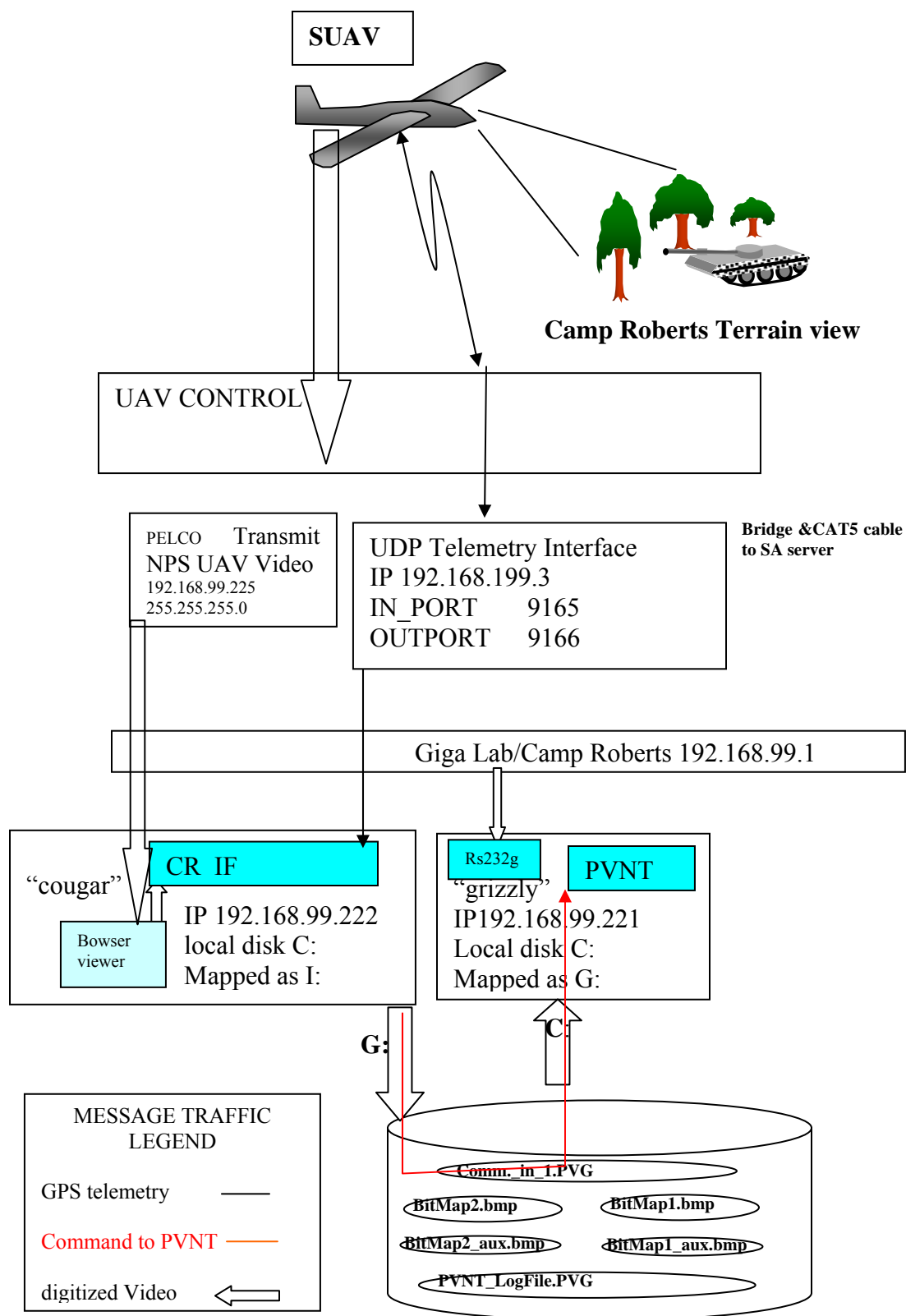


Figure 27. TNT 03-4 FMCSS Schematic Diagram

## 2. Fly the Sensor

Figure 4 shows video returned from the NPS SUAV while tracking a dark colored HMMWV. Prior to this a white SUV acted as the moving target but could not be seen on the white road background. A UDP interface between the SUAV, GCS and PVNT in the MCS provided telemetry from the SUAV and sensor way point as well as control commands in other directions.

The HMMWV appears only as a dot in Figure 28 indicating the need for better resolution. Also noted was the large variation in background view orientation. The frames captured in three second intervals show the view changing by nearly 90 degrees.

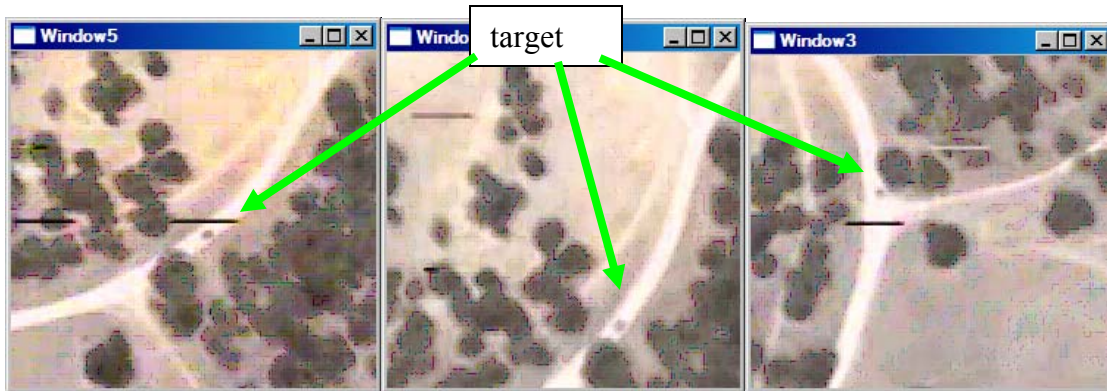


Figure 28. First Tracking HMMWV on Generals Road

It should also be emphasized that spot tracking software that follows the black feature along the white road was not tracking this vehicle. Instead sensor way points were entered on simulated imagery through PVNT along the road at two to three second intervals in order to keep visual contact with the vehicle. The images above showed considerable buffeting and frame-to-frame reorientation.

A better example of the tracking problem is shown in the following five frame clip. The vehicle passes three trees in the upper right edge of window 2 shown below. It is only a small black dot but can be easily seen. For this segment the SUAV is moving in a slow arc around a road point. The first three frames are stable with the camera rotating slowly around a point close to the tree in the lower center.

The fifth frame however shows a jump and the three trees suddenly show up close to the lower right of the frame. The target is not viewable in this frame. In window six

the camera is reoriented toward the lower part of the road, the three trees move up and the target vehicle is again in view.

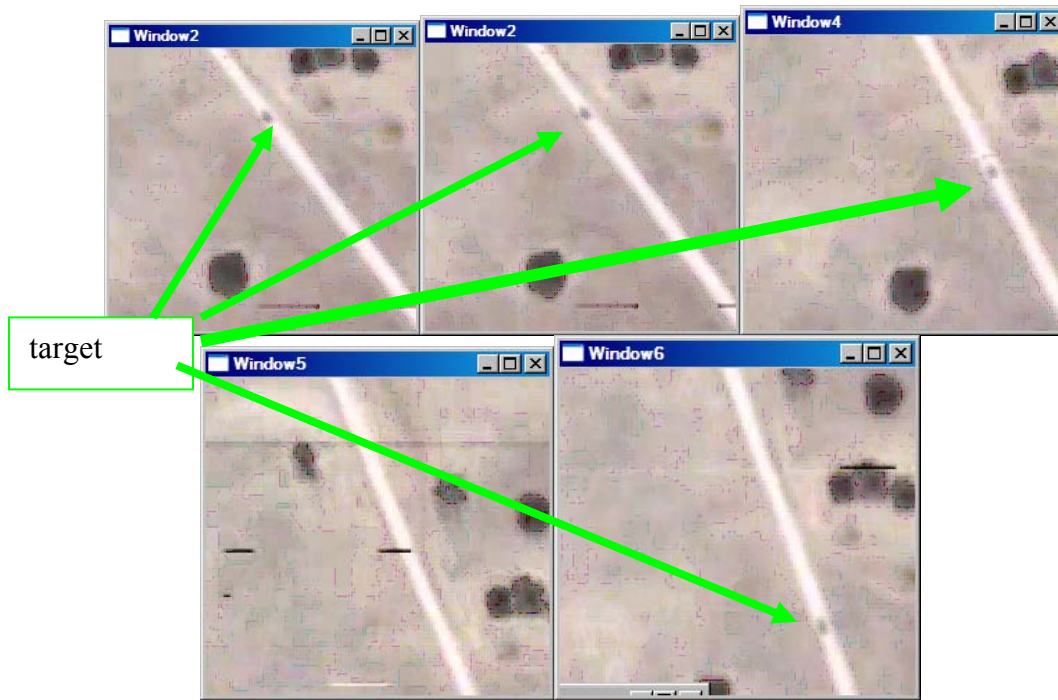


Figure 29. Second Tracking of HMMWV on Generals Road

When the features in window two to six are extracted to perform a flat image rotation and translation, the features did not quite match due to the lack of elevation and projection correction. However, they did match well enough to perform a velocity calculation. A similar calculation could be performed by estimating the target coordinates in each frame separately and performing the velocity calculation mathematically. However, this will require the points to control the camera motion and additional points to follow the target.

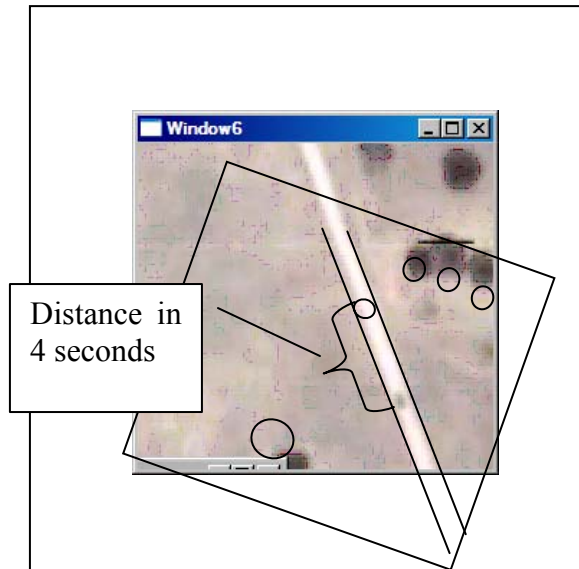


Figure 30. Target Distance Traveled

The experiments conducted were a qualitative test of the ability to fly the sensor and this was accomplished. Quantitative measurements should be taken in follow-on experiments to measure the accuracies and identify correctable sources of inaccuracies. A vehicle outfitted with GPS capable of recording its location is recommended so that comparisons with PVNT generated points can be made.

### 3. Image Stabilization

The goal for this experiment was to verify the compatibility of the VICE mosaic image stability software with the PVNT interface software in order to demonstrate equipment readiness for electronically stabilized image investigations. The CR\_Interface was able to perform mosaic screen capture and synchronize telemetry along with the captured image. The CR\_Interface fixed window proved adequate to capture potential target windows and the BMP format conversion and data transfer to the PVNT downstream processor was accomplished without overloading the VICE machine. Sufficinet screen space on the VICE machine was also verified that it could perform adequate feature identification. Overall, video and telemetry interfaces where completed so that the VICE workstation acted like a PC\_Interface device with live video presented on a mosaic screen<sup>36</sup>.

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<sup>36</sup> A detailed description of the technical modifications is provided in final report entitled: TNT-06-4 Individual Experiment AAR Executive Summary; Dr. Baer, September, 2006.

Figure 26 below shows a screen capture of the VICE mosaic on the right with image trail consisting of six screen image captures on the left. Notice that the mosaic tends to wander and fill the large screen on the right side. The trigger for a new mosaic was a full screen. The VICE software can be set to begin a new mosaic frame every second, but this feature could not be automatically set on the available version and instead was emulated by hand command. A blow up of the windows captured at a one second intervals shows that a fairly well centered picture could be extracted consistently. Figure 31 shows the six trail windows that were captured.

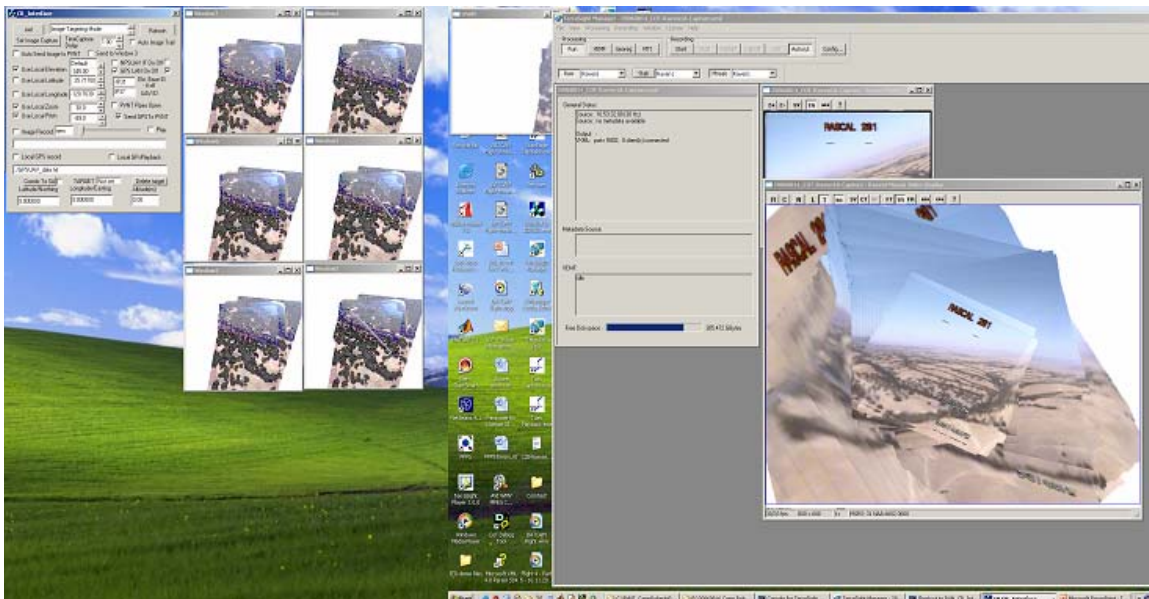


Figure 31. Mosaic Screen Capture



The reader will note that these six one second snapshots still contain considerable



Figure 32. Trail Images Captured

A considerable amount of noise in the form of artifacts was observed in the six one second snapshots shown in Figure 32. A larger mosaic snapshot is shown below in Figure 33 consisting of 10 to 30 slide mosaics. Geographic stability was achieved making this a good technique for viewing; however artifacts are still present in areas where the frames were overlaid. Visual inspection shows considerable distortion in the overlay areas due to edge effects.

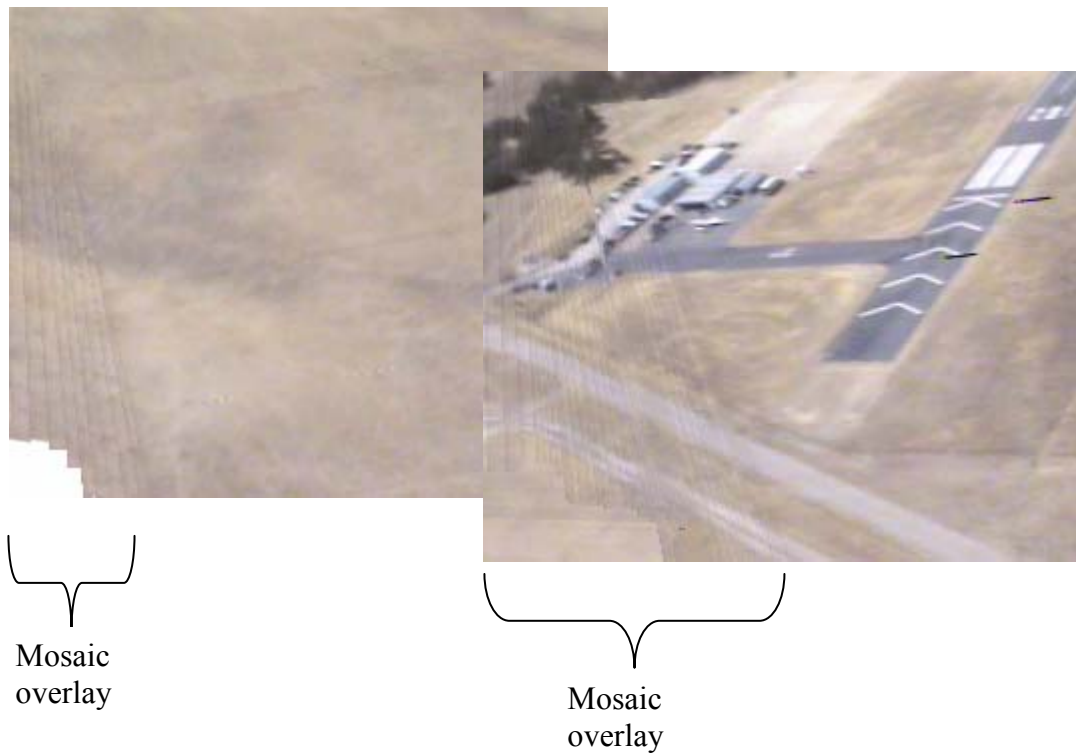
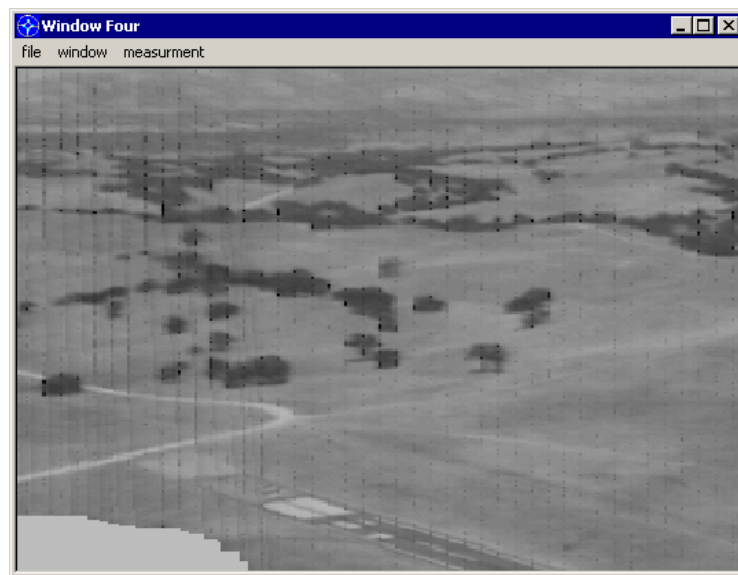


Figure 33. Large Mosaic

When converted to black and white and transferred to PVNT a typical picture looks like the one shown in Figure 34 below. Although line artifacts are visible over the whole picture they are noticeably accentuated in the Mosaic overlay region. Further testing will be required to determine if a computer can actually get any advantage out of the mosaic image.





Mosaic  
overlay

Figure 34. Black and White in PVNT

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## **IX. CONCLUSIONS**

### **A. SUMMARY**

UAS large and small are here to stay. Since the beginning of the Global War on Terror (GWOT) in 2001, the U.S. DoD alone has nearly quadrupled its funding for UAS making it a two billion dollar per year industry. By 2010 this figure is predicted to grow to three billion dollars. The historical and predicted future relevance of UAS was presented in this thesis. Surveillance, target acquisition and reconnaissance (STAR) missions remain the predominant missions that military commanders request UAS to perform. Many other areas including electronic attack (EA), Strike and Suppression of Enemy Air Defense (SEAD), Communication Relays, and Combat Search and Rescue (CSAR) are also expected to be increasingly performed by UAS.

Several technology gaps, particularly those related to STAR missions, were identified. The need for better visual display technologies, better interoperability with other systems and the need to consider the operational support needs over the total life of the system were addressed. A function versus mission table was provided that listed known functions necessary for mission success. It is hoped that this matrix can serve as a guide in the development of future flight and mission control support systems (FMCSS).

An alternative to the current paradigm of designing UAS around the concept of putting a pilot's brain in the cockpit was offered. The concept of "fly-the-sensor" was introduced as a new philosophy to use when designing UAS. The concept shifts the emphasis off the pilot and recommends designs centered on flying the sensor instead of the UAV. As technology advances allowing more vehicle autonomy, this concept will likely permit designs that are less manpower intensive.

Several potential technology solutions were presented that offer the possibility to enhance the likelihood of mission success by reducing the cognitive load on human operators. The thesis presented the argument that designers can achieve more bang for the buck by expending resources on software solutions over computer or airframe hardware solutions. The rapid rate at which of computer hardware technology is

advancing has opened up new possibilities for software solutions to perform functions that are currently being handled by humans.

Finally, two field experiments were conducted to test the feasibility of four potential technology solutions as they pertain to the design of a SUAS FMCSS. The first experiment tested a program that allows synchronized image playback for MCS operators. The objective of this experiment was to give the operator more flexibility by being able to review video instantly instead of needing to retrack an area that was previously observed by the UAV camera. The second experiment tested a program that will allow video from two UAVs to be displayed simultaneously on one monitor. This technology may eventually enable an operator to effectively control multiple UAVs thus reducing the operator to UAV ratio. The third experiment tested the “fly-the-sensor” concept. The experiment demonstrated that a target could be tracked by telling the sensor where to point as opposed to flying the UAV and then pointing the sensor. And finally the last experiment tested the possibility of integrating a commercial software product into the MCS to provide image stability. By reducing the jitter of displayed images the cognitive load on the mission payload operator can be reduced and enable the identification of targets to be accomplished faster.

## APPENDIX A: LIST OF ACRONYMS

AVO	Air Vehicle Operator	MAE	Medium Altitude Endurance
AIAA	American Institute of Aeronautics and Astronautics	MAV	Micro Air Vehicle
AOI	Area of Interest	MCS	Mission Control Station
AOR	Area of Responsibility	MPO	Mission Payload Operator
B/W	Black and White	NRT	Near Real Time
BA	Battlespace Awareness	NPS	Naval Postgraduate School
BDA	Battle Damage Assessment	NDIA	National Defense Industrial Association
BW	Bandwidth	MTI	Moving Target Indicator
C2	Command and Control	NORAD	North American Aerospace Defense Command
C <sup>2</sup>	Command and Control	OEF	Operation Enduring Freedom
C4I	Command, Control, Communication, Computer and Intelligence	OIF	Operation Iraqi Freedom
COCOM	Combatant Commander	NLOS	Non-Line of Sight
COP	Common Operational Picture	VICE	Video Imagery Capability Enhancement
CoT	Cursor-on-Target	OPTEMPO	Operational Tempo
CR	Camp Roberts	NCW	Network Centric Warfare
CSAR	Combat Search and Rescue	NOHD	Nominal Ocular Hazard Distance
DoD	Department of Defense	PDA	Personal Digital Assistant
EA	Electronic Attack	QDR	Quadrenial Defense Review
EM	Electromagnetic	PVNT	Perspective View Nascent Technology
EO	Electro-Optical	RADAR	Radio Detection and Ranging
FA	Force Application	SA	Situational Awareness
FL	Focused Logistics	SECDEF	Secretary of Defense
FLOT	Forward Line of Troops	SUAV	Small Unmanned Air Vehicle
FMCSS	Flight and Mission Control Support System	ROE	Rules of Engagement
FOV	Field of View	RF	Radio Frequency
FP	Force Protection	SUAS	Small Unmanned Aerial System
Gbps	Giga Bit per second	SOCOM	Special Operations Command
GCS	Ground Control Station	SEAD/DEAD	Suppression of Enemy Air Defense/ Destruction of Enemy Air Defense
GIG	Global Information Grid	STANAG	Standardization Agreement
GWOT	Global War on Terror	SME	Subject Matter Expert
HALE	High Altitude Long Endurance	STAR	Surveillance Target Acquisition and Reconnaissance
HIL	Human in the Loop	TCS	Tactical Control System
HMMWV	High Mobility Multipurpose Wheeled Vehicle	TOC	Tactical Operations Center
IADS	Integrated Air Defense System	TNT	Tactical Network Topology
IEEE	Institute of Electrical and Electronics Engineers	TUAS	Tactical Unmanned Aerial Vehicle
IPL	Integrated Priority List	TIPS	Tactical Image Processing Software
IR	Infrared	TCP/IP	Transport Control Protocol/Internet Protocol
ISR	Intelligence, Surveillance and Reconnaissance	UAV	Unmanned Aerial Vehicle
JDAM	Joint Direct Attack Missile	UA	Unmanned Aircraft
JFC	Joint Force Commander	UAS	Unmanned Aerial System
JSRC	Joint Search and Rescue Center	UCAV	Unmanned Combat Aerial Vehicle
LOS	Line-of-Sight	UDP	User Datagram Protocol
MIO	Maritime Interdiction Operations		

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## **LIST OF REFERENCES**

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